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Numerical Study of Super-Critical Accretion Disks

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We performed 2.5-dimensional Special Relativistic Radiation Magnetohydrodynamic simulations to study the super-critical accretion disks and outflows. We found that the super-critical accretion is possible even when the accretion rate is about 10^4 times larger than the Eddington value. The accretion of a large amount of gas leads to liberation of the gravitational energy. Inside accretion disks, the radiation energy dominates over the fluid and magnetic energy. Most of the radiation energy is swallowed by the central black hole, while a small fraction of the radiation energy is transported outward. This radiation flux forms the outflow. The radiation flux force accelerates the outflow, while the radiation drag force prevents from further acceleration. The balance between the radiation flux force and the radiation drag force determines the terminal velocity. The resulting outflow speed is limited by a ceiling, whose terminal velocity is about 30-40% of the light speed.

1. Introduction

Black hole accretion disks are known as the most energetic phenomena in the Universe, such as active galactic nuclei, microquasars, and γ-ray bursts. The gas accretion on to the central black liberates the gravitational energy. Thus the mass accretion rate is the critical parameter to distinguish the accretion mode.

Theoretically, there exist three types of accretion modes depending on the mass accretion rate $\dot{M}$, i.e., radiatively inefficient accretion flow (RIAF), standard accretion disks, and the slim disks in the ascending order of $\dot{M}$. In the RIAF model, the gas and magnetic energy much exceeds the radiation energy because the disk is optically thin. The other two models, on the other hand, the radiation energy is comparable or larger than the (magneto-)fluid energy due to a large optical depth. These models are constructed based on the 1-dimensional approach so that the multi-dimensional effects such as the turbulence inside the accretion disks or the outflow are not taken into account.

For the numerical study, magnetohydrodynamic (MHD) simulations of accretion disks have been performed to study the RIAF state (e.g., [1]). These simulations found that the viscosity is magnetic origin, i.e., the MHD turbulence transports the angular momentum outward and it leads to gas accretion. Also, together with the gas accretion, some fraction of gas is pushed away by the magnetic force and the outflow/jet is formed. Thus the multi-dimensional effect is obvious and has an important role for disk dynamics.

While MHD simulations can reproduce RIAF state, the radiation transport should be taken into account to study the other two accretion modes.

Ohsuga et al. [2] for the first time performed 2.5-dimensional radiation MHD simulations and succeeded in producing three accretion modes. Following this study, Takeuchi et al. [3] showed that the outflow is accelerated by the radiation force and its speed is up to 0.7-0.8*c*, where *c* is the light speed. Although the outflow speed is close to the light speed, their simulation does not take into account the relativistic effect correctly. Recently, authors have been proposed numerical techniques to treat radiation field in the framework of special [4-5] and general relativity [6-10].

In this paper, we performed 2.5 dimensional special relativistic simulations to study relativistic effects for the outflows in the slim disk state.

2. Basic equations and initial model

We solved ordinal special relativistic ideal magnetohydrodynamic equations but the radiation four force G^μ is included as an external force, where μ indicates 0 (time) and 1-3 (space). The radiation four force relates with the radiation moment equations:

$$\partial_t E_r + \partial_j F_r^j = -G^0, \quad (1)$$
$$\partial_t F_r^i + \partial_j P_r^{ij} = -G^i, \quad (2)$$

where

$$G^0 = -\varrho\kappa\left(4\pi\gamma B - \gamma E_r + u_j F^j\right)$$
$$-\rho\sigma[\gamma\left(\gamma^2 E_r + \gamma u_j u_k P_r^{jk} - (2\gamma^2 - 1)u_j F_r^j\right], (3)$$

and

$G^i = -4\pi\rho\kappa B u^i + \varrho(\kappa+\sigma)\left(\gamma F_r^i - u_j P_r^{jk}\right) - \rho\sigma u^i\left(\gamma^2 E_r - 2\gamma u_j F_r^j + u_j u_k P_r^{jk}\right)$. (4)

Here indices (i,j,k) indicate spatial components (1-3). κ and σ are the opacities for absorption and scattering. We solve time evolution of radiation energy density (E_r) and flux (F_r^i), while the radiation stress (P_r^{ij}) is give by the M-1 closure to close the system. Thus the magnetized gas and radiation field are solved self-consistently.

We solve these equations in polar coordinates assuming axisymmetry. At an initial state, the simulation domain is filled with a low density plasma. The magnetized gas is injected far from the central black hole with a finite angular momentum, so that the injected gas form a gas torus around r=60r_S at the equatorial plane. Here r_S is the Schwarzschild radius.

2. Results

Figure 1 shows the radiation energy density (left color) and mass density (right color). The typical mass density in the accretion disk is ~ 0.01g/cm^3 and the corresponding mass accretion rate $\dot{M}$ is 1000 times larger than the critical (Eddington) mass accretion rate $\dot{M}_c$. Thus the supercritical accretion realizes. Due to the liberation of large amount of the gravitational energy, the radiation energy dominates over the fluid energy. The radiation pressure supports the gravity by the central black hole exerting on the disk gas.

Since the magnetized gas is injected during simulations, we can control the mass accretion rate onto the black hole. We confirmed that a steady accretion is possible in the range of $\dot{M}$ ~ $10^{2\text{-}4}$ $\dot{M}_c$.

Next we study the outflow structure for the supercritical accretion. We can see that outflow is emanating from the accretion disks just above the photosphere (solid line in figure 1). The outflow consists of faster jet near the rotation axis and slower outflow with a large opening angle. Their speeds are ~0.4c for the jet and ~0.1c for the outflow. Both of them exceed the escape velocity. Although the jet has a larger speed, the outflow transports much more gas than the jet due to the geometrical effect.

These jet and outflow are accelerated by the radiation force. The radiation flux emanating from the photosphere exerts radiation flux force on the gas. Besides this flux force, the radiation drag force decelerates the gas. The accelerated gas collides with the ambient radiation field and this force prevents from further acceleration. The balance between these two forces determines the terminal velocity. The terminal velocity estimated from the structure of the radiation field is 0.4c for the jet. This result is consistent with the jet speed observed with our simulation.

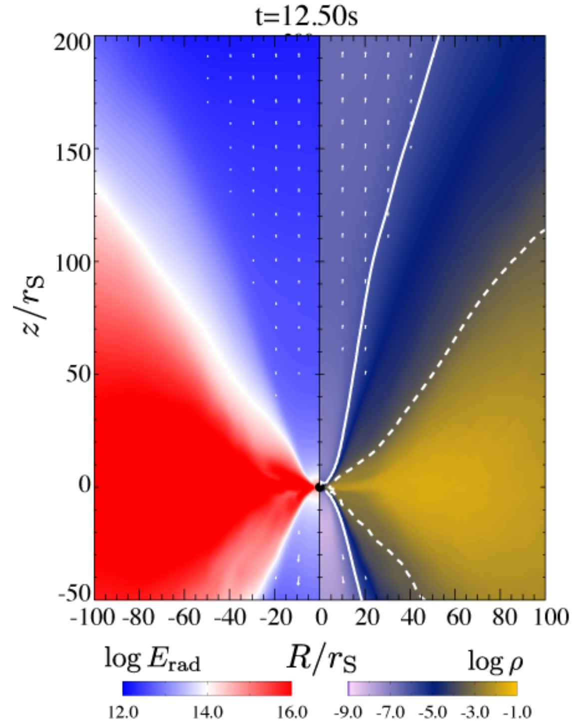

Fig. 1 Results of special relativistic radiation MHD simulation. Color shows radiation energy density and mass density, while arrows show radiation flux and velocity vector for left and right panels, respectively.

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