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Magnetohydrodynamic Simulations of the Co-existence of Hot and Cool Disks in Black Hole Accretion Flows

ブラックホール降着流における高温・低温円盤共存状態の磁気流体シミュレーション

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We carried out global three-dimensional magnetohydrodynamic simulations of black hole accretion flows taking into account the bremsstrahlung cooling. We applied a magnetohydrodynamic code CANS+ based on the HLLD scheme. Higher order accuracy is achieved by MP5 method. When the surface density of the disk exceeds a threshold, hard-to-soft state transition is triggered by the growth of the cooling instability in the outer disk. Since azimuthal magnetic field is amplified as the disk shrinks in the vertical direction by cooling, the disk becomes supported by magnetic pressure. On the other hand, magnetic fields in optically thin, hot, radiatively inefficient accretion flows (RIAF) near the black hole reverse quasi-periodically by disk dynamo. Magnetic reconnection between the dynamo-generated magnetic fields in RIAF and the strong azimuthal magnetic fields in the outer cool disk heats the disk, and enables the co-existence of hot and cool disk, which corresponds to the luminous hard state in black hole candidates.

1. Introduction

Various activities observed in X-ray binaries are driven by mass accretion onto a compact object such as a neutron star or a black hole. The energy source of such activities is the gravitational energy released when rotating matter infalls by losing angular momentum. A rotating disk formed around a gravitating object is called an accretion disk.

In a conventional theory of accretion disks[1], phenomenological α-viscosity is introduced to enable the rotating matter to accrete. Solid curves in figure 1 show the thermal equilibrium curves for a disk obtained by assuming α-viscosity[2]. In the upper branch in an optically thin disk, viscous heating balances with the radial advective cooling. The accretion flow in this branch is called RIAF (Radiatively Inefficient Accretion Flow). In RIAF, the disk stays in hot (ion temperature > 10^{11}K), optically thin state observed as X-ray hard state.

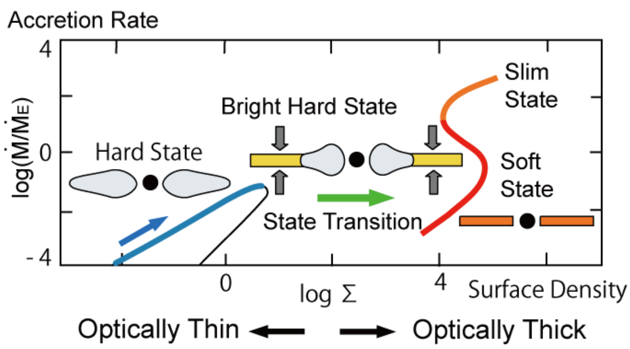

Fig.1. Thermal equilibrium curves of a black hole accretion disk based on [2].

When the surface density of the disk exceeds the upper limit for the existence of RIAF, cooling exceeds viscous heating, so that the disk shrinks in the vertical direction by cooling. Since the disk near the black hole still stays in the hard state, hot and cool disk co-exists. This state may correspond to the bright hard state observed during the hard-to-soft transition.

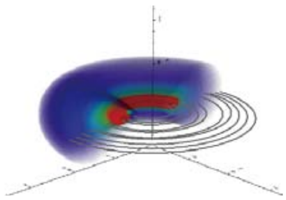

Fig.2. Initial density (color) and magnetic field lines (solid curves).

In this paper, we present the results of global three-dimensional magneto-hydrodynamic (MHD) simulations of black hole accretion flows taking into account the radiative cooling.

2. Numerical Method

We solve the resistive MHD equations in a cylindrical coordinate (r, ϕ, z) by applying CANS+ code based on the HLLD scheme [3]. Fifth order accuracy in space is achieved by MP5 scheme [4]. Figure 2 shows the initial condition. Color shows density, and solid curves show magnetic field lines. We assume that the initial magnetic field is purely azimuthal. The initial ratio of gas pressure to magnetic pressure ($\beta = p_{gas}/p_{mag}$) is β =100. General relativistic effects are simulated by using the pseudo-Newtonian potential. The density maximum of the torus is assumed to be at r=10r_s, where r_s is the Schwarzschild radius. Absorbing boundary condition is applied at r=2r_s.The number of grid points is (N_r,N_ϕ,N_z)=(256,64,256).

3. Results of Disk Dynamo Simulation

Figure 3 shows the evolution of azimuthal magnetic fields obtained by simulations carried out without including the radiative cooling. Magnetic fields are amplified by the growth of the magneto-rotational instability (MRI) [5] and magnetic turbulence. Numerical results indicate that the direction of azimuthal magnetic fields changes quasi-periodically with period about 10 rotation period of the disk. This quasi-periodic dynamo is driven by MRI and Parker instability [6].

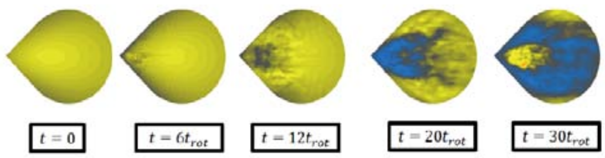

Fig.3. Evolution of azimuthal magnetic fields. Yellow and blue show positive, and negative azimuthal magnetic fields.

4. Numerical Simulations of Cooling Instability

Figure 4 shows a result of simulations carried out by including radiative cooling for optically thin plasma. Cooling term is switched on after 20 rotation period when magnetic turbulence is developed inside the disk. Since the disk density is large enough to trigger the cooling instability, cooling dominated region shrinks in the vertical direction, and cool, dense disk is formed near the equatorial plane.

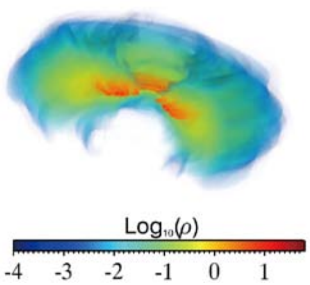

Fig.4. Density after the onset of the cooling instability.

Since the disk shrinks conserving the total azimuthal magnetic flux, magnetic fields are amplified, and the disk becomes supported by magnetic pressure. Figure 5 schematically shows how the magnetic pressure dominant (low- β) region is formed. As the accretion rate increases, the density of the hot, RIAF in the outer region exceeds the threshold for the onset of the cooling instability, magnetically supported, cool, dense region is formed. These results are consistent with Machida et al. (2006)[7] carried out by using the MHD code based on the modified Lax-Wendroff scheme.

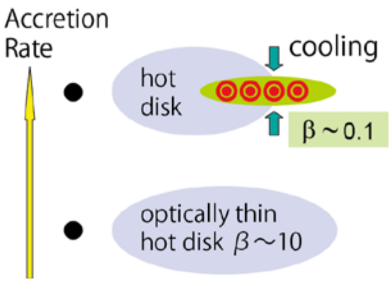

Fig.5. A schematic picture showing the formation of magnetically supported cool disk by cooling instability..

By applying CANS+ code, we carried out longer time-scale simulations after the onset of the cooling instability, and found that magnetic reconnection between the dynamo fields near the black hole and strong azimuthal magnetic fields in the outer disk reconnect, and heat up the plasma. Furthermore, the magnetic energy release forms jet-like outflows ejected from the disk.

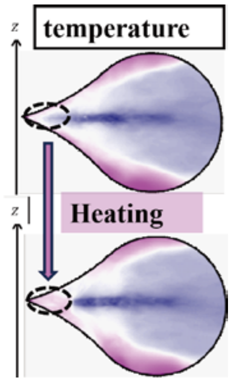

Fig.6. Heating of the inner disk by release of the magnetic energy.

5. Summary

We found that during the hard-to-soft transition, magnetic energy release around the interface between the cool outer disk and hot inner disk heats the disk. When this heating balances with radiative cooling, the disk can stay in luminous hard state.

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