MHD SIMULATIONS OF JETS FROM ACCRETION DISKS

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Abstract. We present the MHD simulation including accretion flows in disks, acceleration of outflows from disks, and collimation of the outflows self-consistently. Although it was considered that this kind of simulations only shows the transient phenomena of jets, we found that the outflow and accretion flow reached a quasi-steady state by performing a long-term calculation in a large calculation region. Though the final stage is not exactly the steady state, the acceleration and collimation mechanisms of the outflow were the same as those of the steady theory. The scale of the calculation is approaching to the scale that was observed by the VLBI technique, which provides the current highest resolution for YSO jets.

Keywords: MHD, jet, numerical simulation

1. Introduction

Time-dependent MHD simulations of jet models including dynamic accretion of disks were first studied by Uchida and Shibata (1985) and Shibata and Uchida (1986). However, the calculation regions of those simulations were restricted to nearby the inner edges of the disks, and the calculation times were limited to a few rotations of the disks. Therefore, it was sometimes considered that this kind of simulations only shows the transient phenomena of jets and is different from the steady theory of the MHD outflows studied by Blandford and Payne (1982), Pudritz and Norman (1986) and others.

Kudoh, Matsumoto and Shibata (1998) performed Uchida and Shibata's type simulations that was improved by Matsumoto et al. (1996). They found that the acceleration mechanism of Uchida and Shibata's jet is the same as that of the steady jet, though it is not exactly in the steady state. However, they did not discuss the collimation mechanism of the jet because the calculation time and region were still not enough.

In this article, we are going to present the large-scale long-term Uchida and Shibata type simulation, including accretion flows of disks, acceleration of outflows from disks, and collimation of the outflows self-consistently.

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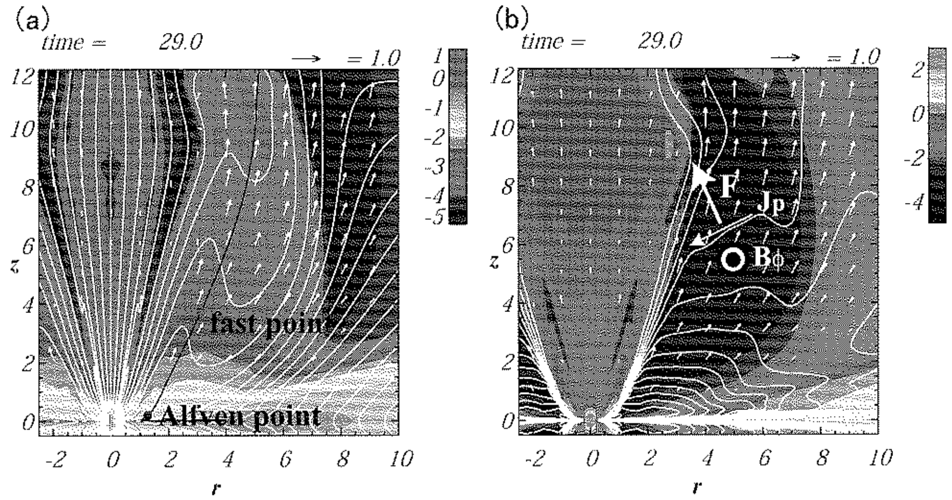

Figure 1. (a) Color shows the density in logarithmic scale. White lines show the poloidal magnetic field lines. A black line shows one of the stream lines. The arrows show the poloidal velocity. On the stream line, the fast magnetosonic point and Alfvén point are denoted. (b) Color shows the ratio of gas pressure to magnetic pressure in logarithmic scale. White lines show the lines of poloidal current density (J_p). Arrow shows the poloidal velocity. B_ϕ is the toroidal component of the magnetic field, which is perpendicular to the $r - z$ plane. F shows the Lorentz force generated by $J_p \times B_\phi$.

2. Methods

Our simulations made the following assumptions: (1) axial symmetry around the rotational axis, including the azimuthal components of the velocity and the magnetic field (i.e., 2.5 dimensional approximation); (2) ideal MHD; (3) a specific heat ratio of $\gamma = 5/3$; (4) a point-mass gravitational potential, with the disk self-gravity being neglected.

As an initial condition, we assumed a low-temperature equilibrium disk rotating in a central point mass gravitational potential. The mass distribution outside the disk was assumed to be that of a high-temperature isothermal corona in hydrostatic equilibrium without rotation. The initial magnetic field was assumed to be a potential magnetic field threading the disk.

3. Results

Figure 1(a) shows the snapshot of the density after about 7 Keplerian rotations of the initial disk's inner-edge which is assumed to be near the star. White lines show magnetic field lines and a black line shows one of the stream lines. In contrast to the usual 'steady theory' of jet formation, the magnetic field lines were not parallel to the stream lines. This is because that the magnetic field lines were being conveyed to a central star by the disk accretion-flow which was caused by the angular momentum transfer from the disk to the outflow through the magnetic field. However, time evolution of the stream lines showed that the outflow was in quasi-steady state after several rotations of the disk. The outflow was accelerated to the super-magnetosonic speed, and the terminal speed was on the order of the Keplerian speed. We confirmed that the outflow was accelerated by the centrifugal force and magnetic Lorenz force. The gas pressure gradient was negligible in the outflow.

Figure 1(b) shows the ratio of gas pressure to magnetic pressure. White lines show the lines of poloidal current density (J_p). Because the toroidal magnetic field (B_ϕ) was generated by the rotation, the magnetic pressure was dominated in the outflow, though the initial magnetic pressure was comparable to the gas pressure. The Lorentz force (F) was generated by the poloidal current density and toroidal magnetic field. The parallel component of this force to the stream line accelerated the jet, and the perpendicular component to the stream line collimated the jet. We found that the perpendicular component of the force had an approximated force balance with the inertial force of the outflow. This force balance is consistent with the paraboloidal type collimation discussed in Sakurai (1985) and Heyvaerts and Norman (1989).

4. Discussion

In contrast to Uchida and Shibata's simulations, Ouyed and Pudritz (1997), Ustyugova et al. (1999), Krasnopolsky et al. (1999) and others performed large-scale long-term MHD simulations of jet formation from disks. Some of them also found that jets reached steady states. The difference between our study and theirs is the treatment of the disk. We allowed the disk to fall into the central star when the disk loses its angular momentum through magnetic field. On the other hand, Ouyed and Pudritz (1997) and others had an assumption of fixed rotating disks without taking into account accretion flows in disks. We think that it is important to take into account accretion flows in the simulation, because the fixed rotating disk assumption is not consistent with the angular momentum transfer between disks and outflows.

Although our simulation is larger-scale and longer-term simulation than previous Uchida and Shibata's type simulation, the maximum scale of the simulation is still about 10 times smaller than the scale that was observed by the VLBI technique which provides the current highest resolution for YSO jets. We expect that the scale of the numerical simulation will be larger in future according to the improvement of both numerical scheme and machine power. Moreover, including dissipation mechanisms, such as viscosity, resistivity, and radiative loss into the simulation will be a future work.

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