Magnetically Driven Outflows from Accretion Disks
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Abstract
This is the first magnetohydrodynamic (MHD) numerical simulation including accretion of a disk, ejection of a jet, acceleration and collimation of the jet, and formation of a bow shock. We extend the computational region to about 100 times larger than the radius of central star to investigate the collimation of jet and a formation of a bow shock. (It is about 10 times larger than those of the previous works.) We found that both the magnetic field lines and stream lines are collimated by the pinch effect of the toroidal component of the magnetic field that is generated by the differential rotation in the disk. Finally, the bow shock is formed at the head of the jet by the 'piston effect' of the toroidal component of the magnetic field. The result of the large scale simulation should be compared to the high resolution observation by VLBI.

1 Introduction
Magnetically driven jets from accretion disks have been considered as the most promising models for astrophysical jets which are observed in young stellar objects (e.g., Uchida & Shibata 1985, Pudritz & Norman 1986, Shu et al. 1994, Kudoh & Shibata 1995, 1997a; 1997b). Time dependent numerical simulations are first performed by Uchida & Shibata (1985) and Shibata & Uchida (1986; 1989; 1990) to study how jets are accelerated from an accretion disk that is initially threaded by vertical magnetic field lines. These MHD numerical simulations of magnetically driven outflows from accretion disks concentrated to the acceleration mechanism of MHD jets, and their computational box are limited to the ejection regions of jets (Matsumoto et al. 1994, Kudoh, Matsumoto & Shibata 1998). In order to investigate the collimation of jet and a formation of a bow shock, we have to extend calculating region. Recently, Ouyed, Pudritz & Stone (1997) performed large scale simulations of MHD jets. However, the disk accretion is not included in their simulation. (They treated the disk as a boundary condition.) In this paper, we first performed a large scale MHD numerical simulation of a jet from an accretion disk, including accretion process itself, to a bow shock formed ahead of a propagating jet, by extending the simulation box 10 times larger than before.

2 Results
Fig. 1 shows the time evolution of a jet from an accretion disk. Upper left panel shows the initial condition. Initial magnetic field is assumed to be a potential magnetic field (Cao & Spruit 1994). The shape of the field line is paraboloidal in large scale. The energy density of initial magnetic field is almost the same as the gas pressure in the disk. The temperature of corona is assumed to be decreasing with increasing of radial distance when $\frac{r^2 + z^2}{1} > 1$. Instead of the real star, high density region, which is in a hydrostatic equilibrium with uniform temperature, is assumed in the central region. The disk is initially in a dynamical equilibrium with almost Keplerian rotation speed (Abramowicz, Jaroszynski, & Sikora 1978). Its density is about 1000 times larger than that of the corona. At first, the disk falls to the central region losing its angular momentum by the magnetic braking. As the angle between the magnetic field line and the disk decreases, the jet is ejected from the disk by the Lorentz force (Blandford & Payne 1982, Kudoh et al. 1998).

Figure 1: Time evolution of the density. White vertical lines are magnetic field lines. Arrows show the poloidal velocity vectors normalized by the Keplerian velocity at $(r, z) = (1, 0)$. The radius of the central star is about 0.2 in this normalized length. The time $= 2\pi$ corresponds to one Keplerian orbit at $(r, z) = (1, 0)$.

Figure 2: The density in different scales at time=29. White vertical lines are magnetic field lines. Arrows show the poloidal velocity vectors normalized by the Keplerian velocity at $(r, z) = (1, 0)$. 

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Figure 3: The density, pressure, and magnetic pressure of the toroidal magnetic field at time = 29. White vertical lines are magnetic field lines. Arrows show the poloidal velocity vectors normalized by the Keplerian velocity at $(r, z) = (1, 0)$. The red lines show streamlines.

Fig. 2 shows the density in different scales at time = 29. The calculation region of the previous work (∂udr) is as small as the lowest panel of Fig. 2. The large scale calculation shows the collimation of the outflow from a disk and the formation of a bow shock at the top of the jet.

Fig. 3 shows the density, pressure and magnetic pressure of the toroidal magnetic field at time = 29. We can see that the bow shock is formed at the head of the jet where the density and pressure are enhanced by the shock. The bow shock is formed by the 'piston effect' of the toroidal component of the magnetic field. The toroidal component of the magnetic field pushes the coronal gas, and the shock is formed ahead of it. The magnetic pressure is larger than the gas pressure in the shocked region (Fig. 4). It means that the bow shock is a gas pressure dominated fast magnetosonic shock. We can see another shock appeared near $z \sim 12$. This is the slow magnetosonic shock which is produced in a low $\beta$ region, where $\beta$ is the ratio of gas pressure to magnetic pressure.

3 Discussion

Recently, the VLBI observation by Furuya et al. (1999) found a very small scale bipolar flow structure which is a 10 AU-scale jet ejected from very close to a protostar. They also found a 'U shaped' structure which may be a bow shock or a part of a bow shock. The scale of the jet and shock is about 1000 times larger than the radius of the protostar. It is about 10 times larger than the computational region of our numerical simulation. We believe that the shock and jet observed by Furuya et al. (1999) can be compared to our MHD numerical simulations. In the jets from young stellar objects, however, the radiative cooling may be important because of the high density. If the radiative cooling is effective in the shocked region, the bow shock is not stable and its shape would be distorted (Blondin & Koerwer 1998). The 'U shaped' structure may be produced by the instability of the shock. We will include radiative cooling in our simulation for the comparison with the observations.

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