Resistive Magnetohydrodynamic Simulations of Jet Formation
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Abstract
We carried out 2.5-dimensional resistive magnetohydrodynamic simulations to study the effects of magnetic diffusivity on the magnetically driven mass accretion and jet formation. When a constant angular momentum torus is threaded by large-scale vertical magnetic fields, the angular momentum of the torus is extracted due to magnetic braking and the torus medium falls toward the central region. The large-scale magnetic fields twisted by the infalling matter drives bipolar jets. We studied the dependence of the mass accretion rate and the mass outflow rate on magnetic diffusivity \( \eta_0 < 10^{-3} \), which is the reference radius and \( \gamma \) is the Keplarian rotation speed at \( r = r_0 \). We found that (1) in non-diffusive or low diffusive model \( (\eta_0 < 10^{-3}) \), the mass accretion and the jet formation take place intermittently, (2) in mildly diffusive model \( (10^{-3} < \eta_0 < 10^{-2}) \), the system evolves toward a quasi-steady state, (3) in highly diffusive model \( (\eta_0 > 10^{-2}) \), accretion/mass outflow rate reduces with \( \eta_0 \) and approaches 0.

1 Introduction
Magnetically driven outflows from accretion disks are the most promising models of acceleration and collimation of jets/winds in star forming regions or in active galactic nuclei. By assuming steady axisymmetric bipolar outflow, it has been shown that when the magnetic field lines make angles less than 60 degrees from the equatorial plane, magneto-centrifugally driven outflow of matter can emanate from the surface of the disk (Blandford, Payne 1982). Nonlinear, two-dimensional MHD simulations of jet formation from accretion disks including the effects of back reaction of jet formation on disks have been carried out by Uchida, Shibata (1985) and Shibata, Uchida (1986). They showed that jets/winds are formed by the relaxation of magnetic twists generated by the rotation of the disk. Matsumoto et al. (1996) carried out 2D MHD simulations of a torus threaded by poloidal magnetic fields and showed that the surface layer of the torus accretes faster than the equatorial region like an avalanche because magnetic braking most efficiently extracts angular momentum from that layer.

Most of the nonsteady models of magnetohydrodynamic jet formation from an accretion disk assumed ideal MHD. However, it is hard to obtain the steady solutions of magnetically driven winds/jets including the accretion disk because when the resistivity is not included, the accretion disk may be highly nonsteady due to the surface avalanching flow and generation of turbulence by the magnetorotational instability inside the disk. From the 3D simulation, it was shown that the turbulence generates effective magnetic diffusivity which can suppress the growth of the magnetorotational instability. It is possible that an accretion disk is in a marginally stable state in which the magnetic turbulence is maintained in a marginal level over which turbulent magnetic diffusivity kills the growth of the magnetorotational instability (Matsumoto, Tajima).

In weakly ionized disks, since the Spitzer type resistivity itself becomes large, it can affect the growth of the magnetorotational instability (Sano et al. 1998). In this paper we introduce resistivity to simulate the effects of either the turbulent magnetic diffusivity or the resistivity in very weakly ionized disks on the formation of jets. When the disk is resistive, the magnetic field lines do not rotate with the same angular speed as the disk matter, and thus it suppresses the injection of magnetic helicity (magnetic twists) and the magneto-centrifugal acceleration. We would like to study the dependence of the mass accretion rate and mass outflow rate and jet speed on resistivity (or turbulent diffusivity) by 2D axisymmetric resistive MHD simulations.

2 Numerical Simulations and Results
A schematic picture of our model and the numerically simulated region are shown in Figure 1. We assume that a central gravitating object is surrounded by a polytropic, constant angular momentum torus threaded by large-scale vertical magnetic fields (see Matsumoto et al. 1996). We incorporated the effects of turbulent magnetic diffusivity by including an uniform resistivity \( \eta_0 = \eta_0/(\gamma r_0) \). Here, \( \eta_0 \) is the radius where the equatorial density of the torus is maximum and \( \gamma \) is the Keplarian rotation speed at \( r = r_0 \). Other model parameters are \( B_{0\phi} = c_B/(\gamma r_0) \) and \( B_{0\phi} = v_A/(\gamma r_0) \), where \( c_B \) and \( v_A \) are the sound speed and the Alfven speed at \( (r, z) = (r_0, 0) \), respectively, and \( \gamma \) is the adiabatic index which we take \( \gamma = 5/3 \). The efficiency of magnetic braking depends on the ratio of the halo density to the torus density \( \rho_h/\rho_t \) where \( \rho_h \) is the halo density at \( (r, z) = (0, r_0) \) and \( \rho_t \) is the maximum density of the torus. We introduce results for three models shown in Table 1. Other parameters are \( B_{0\phi} = 0.05, B_{0\phi} = 5 \times 10^{-4} \) and \( \eta_0 / \rho_0 = 10^{-3} \) for all models.

Table 1: The numerical value of magnetic diffusivity \( \eta_0 \) for non-diffusive, mildly diffusive and highly diffusive models.

<table>
<thead>
<tr>
<th>Model</th>
<th>( \eta_0 )</th>
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<tbody>
<tr>
<td>Non-diffusive</td>
<td>0</td>
</tr>
<tr>
<td>Mildly diffusive</td>
<td>( 10^{-2} )</td>
</tr>
<tr>
<td>Highly diffusive</td>
<td>( 3.3 \times 10^{-3} )</td>
</tr>
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Figure 2 shows the distribution of temperature (grey scale), magnetic field lines (white curves) and velocity vectors (arrows) in three models. In non-diffusive model (Figure 2(a)), the poloidal magnetic field lines show that the surface layer of the torus falls faster than the equatorial plane due to magnetic braking and forms a jet because some part of the surface layer moves outward by gaining angular momentum and prevents the infall of the disk material. After the initial avalanche ceases, the second avalanche-like accretion leads to the second jet ejection. On the other hand, in mildly diffusive model (Figure 2(b)), the surface avalanche is not so evident as in the non-diffusive model but the jet width is larger than that of non-diffusive model. The mass accretion and the mass outflow take place continuously. The magnetic field lines are less deformed than those of non-diffusive model. In highly diffusive model (Figure 2(c)), the magnetic field lines are deformed only slightly and only weak outflow with velocity \( v \sim 0.3v_{K0} \) appears.

Figure 3(a) shows the time dependence of the mass accretion rate \( \dot{M}_{acc} = -4 \pi \int_0^1 (r/r_0) (\rho/\rho_0) (v_\phi/r_0 c_\phi) d(r/z) \) at \( r = 0.3r_0 \) for all models. When \( t > 0 \) the time averaged accretion rate of non-diffusive model and mildly diffusive model takes almost the same value independent of \( \eta_0 \), although the accretion rate increases more rapidly in non-diffusive model. The accretion rate of mildly diffusive model approaches a
quasi-steady value but the peak accretion rate is smaller than non-diffusive model. Almost no accretion takes place in the highly diffusive model. Figure 3(b) shows the mass outflow rate $\dot{M}_{out} = 4 \pi \int_0^{r_0} (r/r_0)(\rho/\rho_0)(v_z/v_0) \, r \, dr$ at $z = 5.0 r_0$. In non-diffusive model, the mass outflow rate has several peaks and the jet production takes place episodically. In mildly diffusive model, however, the mass outflow rate increases monotonically with time and approaches a quasi-steady value. In highly diffusive model, the mass outflow rate approaches 0.

3 Discussion

We have studied the effects of resistivity on the magnetically driven accretion and jet formation from a torus threaded by large-scale poloidal magnetic fields. In non-diffusive model, surface layer of the torus infalls faster than the equatorial part like an avalanche and magnetically driven jet appears. The jet formation and mass accretion take place episodically. This episodic accretion occurs because some part of the torus moves radially outward by gaining angular momentum and hinders the mass outside it to accrete. The magnetorotational instability developing inside the torus also helps to create the episodic behavior. The speed of the jet nearly equals to the Keplerian rotation speed. In mildly diffusive model, the torus approaches a quasi-steady state without showing episodic behavior. In highly diffusive model, no mass accretion and jet formation take place.

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References

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