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Global three-dimensional magnetohydrodynamic simulations of differential rotating disks : formation of quasi-steady Keplerian disk

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We present numerical results of long time-scale three-dimensional global resistive magneto-hydrodynamic (MHD) simulations of a disk initially threaded by toroidal magnetic fields. After several rotation period, the disk becomes turbulent due to the growth of the magneto-rotational instability. Since the angular momentum is efficiently transported outward by Maxwell stress, the disk becomes flattened and matter accretes to the central object. When the magnetic Reynolds number Rm > 100, the system approached a quasi-steady state with beta=(gas pressure)/(magnetic pressure)=5-10 almost independent of Rm. The effective value of the "alpha" parameter in accretion disk theory is alpha=0.01-0.1, consistent with the observations.

When matter with angular momentum accretes to gravitating objects such as black hole, neutron stars, or young stars, it forms a differentially rotating disk called "accretion disks". Magnetic fields in differentially rotating disks play essential roles in the angular momentum transport which enable the accretion and various activities such as X-ray flares and jet formation. Recently, the importance of the magneto-rotational instability in differentially rotating disks has been widely recognized. Local three-dimensional MHD simulations (e.g., Hawley et al. 1995) revealed that the disk becomes turbulent due to the nonlinear growth of the magneto-rotational instability. However, local simulations could not give the exact values of the angular momentum transport rate because numerical results depended on the size of the simulation box.

Thus we carried out global three-dimensional magneto-hydrodynamic (MHD) simulations of a disk. The initial model we assume is an equilibrium model of an axisymmetric torus surrounding the central object threaded by toroidal magnetic fields. By applying "astrophysical rotating plasma simulator" which consists of parallelized high-performance 3D MHD codes and plug-in modules such as resistivity, we carried out simulations for time scale long enough to approach the quasi-steady state.

We studied the dependence of numerical results on the initial magnetic field strength, initial angular momentum distribution, and initial magnetic Reynolds number. We present the results of the simulations starting from a constant angular momentum torus. After several rotation period, growth of the magneto-rotational instability generates turbulence in the disk. The vortex motions of the turbulent eddies tangle magnetic field lines in the torus. Since the resulting Maxwell stress transports angular momentum outward, the torus becomes disk-like shape and the angular momentum are redistributed. The disk material which lost angular momentum gradually falls into the central object. On the other hand, the matter in the outer region of the torus expands by gaining angular momentum. The effective value of the phenomenological viscous "alpha" parameter which appears in the accretion disk theory is found to be between 0.01 and 0.1, consistent with the values estimated by comparing the theory and observations of dwarf nova.

When the initial magnetic field is weak, we found that the magnetic fields are amplified and saturates when the magnetic energy is about 10% of the thermal energy (beta = 5-10). When the initial magnetic energy is comparable to the thermal energy, the disk also approaches high beta (beta = 5-10) state due to buoyant escape of magnetic flux from the disk. The saturation level of the magnetic energy is almost independent of the magnetic Reynolds number Rm so long as Rm > 100.

The radial structure of the disk is different from that of the advection disk models but close to the convection dominated accretion flow (CDAF). The occurrence of convective motion in the MHD disk (Machida et al. 2001) is also briefly discussed.