Global 3D simulations of magnetohydrodynamic turbulence, dynamo, and state transitions in astrophysical rotating disks

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We have developed a global three-dimensional magnetohydrodynamic (MHD) code to simulate rotating plasmas and applied it study the growth and saturation of MHD turbulence, amplification of magnetic fields, and state transitions in astrophysical rotating disks.

Hubble space telescope revealed the existence of a torus rotating around a protostar and bipolar jets. Disks and jets are also observed in active galactic nuclei. Since gravitational energy of the infalling matter can be converted to magnetic and radiation energies in these disks, these rotating disks (accretion disks) can be the origin of various activities such as X-ray emission and jet formation.

In accretion disks, centrifugal force and pressure gradient force balance with the gravity of the central object. In order for the matter to accrete, angular momentum of the rotating matter should be transported. Conventional theory of accretion disks were constructed by parametrizing this transport coefficient. The angular momentum transport should be very efficient in order to explain the observations. The origin of the efficient angular momentum transport had been a puzzle. One possibility is the Kelvin-Helmholtz instability in differentially rotating disks. However, J. Hawley (1991) showed by 3D hydrodynamical simulations that it is hard to get such a high angular momentum transport rate.

Another possibility is the magnetic turbulence. Balbus and Hawley (1991) pointed out that when a differentially rotating plasma is threaded by weak magnetic fields, magnetorotational instability (MRI) grows in time scale of rotation. The origin of this instability is the angular momentum transport by Maxwell stress.

We developed astrophysical rotating plasma simulator (ARPS) by which we can carry out global 3D MHD simulations of rotating plasmas and carried out global 3D MHD simulations including the whole disk. Initial state is a constant angular momentum torus threaded by weak toroidal magnetic fields. We found that MRI drives magnetic turbulence in the disk and that part of the torus material loses angular momentum by Maxwell stress exerted by the turbulent magnetic fields and accretes to the central object. We successfully reproduced the formation process of accretion disks. The plasma beta in quasi-steady state is about 10. The efficiency of the angular momentum transport agreed with those estimated by comparing the theory of accretion disks and observations (Matsumoto 1999; Machida et al. 2000). We now can study the evolution of accretion disks without introducing the phenomenological parameter.

Machida and Matsumoto (2003) carried out long time-scale simulations of black hole accretion flows by applying ARPS. We found that accreting matter creates bisymmetric spiral magnetic fields and current sheets by stretching the magnetic field lines. Magnetic reconnection taking place in these current sheets can explain X-ray flares (X-ray shots) observed in black hole candidates. We also successfully reproduced observed 1/f-noize like X-ray fluctuations by turbulent magnetic reconnection inside the disk.

We also report the results of simulations of state transitions of black hole accretion flows between X-ray hard states and X-ray soft states. The origin of this transition is the change of mass accretion rate and thermal instability due to radiative cooling.