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Astrophysical Dynamos in Rotating Disks - Magnetohydrodynamic Simulations of Accretion Disks and Galactic Gas Disks

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Magnetic fields play essential roles in various activities of accretion disks and galactic gas disks. Since Balbus and Hawley (1991) pointed out the importance of magneto-rotational instability (MRI) in differentially rotating disks, local and global three-dimensional magnetohydrodynamic (MHD) simulations have been carried out. It turned out that the Maxwell stress enhanced by the MHD turbulence generated by MRI transports angular momentum efficiently and enables the accretion of the disk material. When the initial magnetic field of the disk is weak, magnetic field is amplified by MRI and saturates when plasma beta is around 10.

Longer time scale MHD simulations of differentially rotating disks revealed that the direction of the mean azimuthal magnetic fields changes quasi-periodically. The field reversal is driven by the buoyant rise of magnetic flux due to the Parker instability. The time scale of the field reversal is about 10 rotation period at each radius (e.g., Shi et al. 2010, Machida et al. 2013).

We have developed a three-dimensional MHD code CANS+ in which the resistive MHD equations are solved by HLLD scheme (Miyoshi and Kusano 2005). Higher order accuracy is attained by MP5 scheme (Suresh and Huynh 1997). The hyperbolic divergence cleaning method (Dedner et al. 2002) is applied to approximately satisfy the divergence free condition. Figure 1 shows the density distribution of the disk obtained by global 3D MHD simulations. Figure 2 shows a numerically obtained butterfly diagram of the galactic dynamo.

We found that when the accretion disk changes from a hot state (X-ray hard state) to a cool state (X-ray soft state) by increase of the accretion rate, strongly magnetized region is formed around the equatorial plane because the disk shrinks in the vertical direction by radiative cooling. Magnetic reconnection taking place in the interface between the hot disk and the strongly magnetized cool disk keeps the disk in the intermediate state between the soft state and the hard state. Jets observed during this transition can be explained by the magnetic energy release . The coexistence of the cool disk and the hot disk is consistent with the X-ray time variations observed in Seyfert galaxies.

By high resolution global 3D MHD simulations of solar dynamo, Hotta et al. (2016) showed that the coherent magnetic fields are destroyed by turbulence when numerical resolution is high enough to simulate the turbulence. Meanwhile, coherent magnetic fields are recovered when the numerical resolution becomes higher because the strong local magnetic fields enhanced by the turbulence suppress turbulence. The numerical resolution of disk simulations is not high enough to confirm this process in astrophysical disks. We discuss the relevance of current low resolution MHD simulations of disk dynamos and prospects for high resolution simulations. We also discuss the effects of non-thermal particles (cosmic rays) on dynamos in galactic gas disks.

References

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Figure 1 Density distribution before and after the onset of the cooling instability

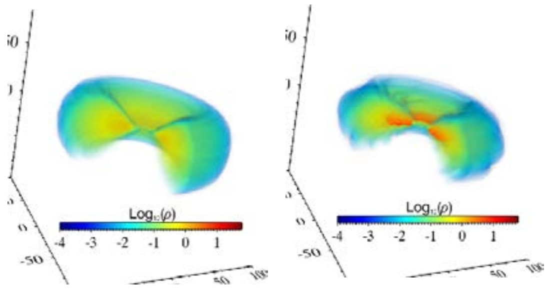

Figure 2 A butterfly diagram of galactic dynamo. Vertical axis shows height from the equatorial plane. Color shows mean azimuthal magnetic fields. Field directions are opposite in red region and blue region.