論文の内容の要旨

Interplay between Magnetorotational Instability and Magnetic Reconnection in Collisionless Accretion Disks

(無衝突降着円盤に於ける磁気回転不安定性と磁気リコネクションの相互作用)

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Transport of angular momentum is one of the essential problems in accretion disk physics since rotating matters must lose angular momentum when they "accrete" into the central star. For the efficient transport of angular momentum, a strong viscosity provided by turbulence in the disk is considered to be important. Magnetorotational instability (MRI), which is a main topic of this dissertation, is believed to drive a strong turbulence in the disk and has been studied by numerical simulations for several decades. To estimate the efficiency of the angular momentum transport, evaluation of the saturated state of MRI-driven turbulence is required. Since MRI provides strong dynamo process and enhances magnetic field, dissipation process is also important for the saturation of MRI-driven turbulence. Magnetic reconnection, which is another topic of this dissertation is considered to be a promising agent for the dissipation in disk turbulence.

Until now studies of disk turbulence has been carried out under MHD approximation which mainly assumes that the disk is constituted with "collisional" plasma. However, recent observations of Sgr A* which lies in the center of our galaxy, suggest that this assumption is not necessarily valid. This object is considered to be constituted with supermassive black hole with the mass of several $10^6 M_\odot$ and has an accretion disk around the black hole. The estimated temperature of the ions in the disk is much higher than that of electrons which suggests that there are no efficient relaxation process between these two components and thus, this disk is considered

to be "collisionless". Since the relaxation process is very weak in the collisionless plasma, isotropy in the particle distribution is no longer valid. "Anisotropy" in the pressure which is one of the well known modification in collisionless plasma greatly modulates the feature of magnetic tension which act as a restoring force in MRI. Motivated by these facts, several attempts to include "collisionless" effects in the MRI simulation have been made by applying CGL (Chew-Goldberger-Low) approximation in MHD equations and assuming isotropization process via kinetic instabilities.

Since the early attempts were based on fluid framework, those kinetic effects are not exactly taken into account. Recently by using 2.5 dimensional PIC simulations, kinetic process is included with self-consistent manner. However, since the time and spacial scale of the PIC simulation is restricted by electron dynamics it requires massive computational resources for the further long term 3 dimensional calculation. Considering the fact that in the actual disks ions are much hotter than electrons, hybrid framework, which treats only the ions as particles and assumes the electrons as charge neutralizing fluid, would provide a more robust approach for the collisionless accretion disk simulation.

In this study we developed a hybrid code to investigate the local evolution of collisionless differentially rotating system. By introducing the finite electron mass, we have overcome a numerical difficulties with which the hybrid code encounters in a problem which involves dynamical change of the plasma density and the magnetic field, such as MRI. By using this new hybrid code we have investigated a heavily non-linear stage of 2.5 dimensional MRI. In the non-linear stage, channel flows driven by MRI were corrupted due to the magnetic reconnection and formation of magnetic islands are observed. We have also evaluated the efficiency of the angular momentum transport in this non-linear stage from the stress components. These results are discussed in Chapter 2.

Motivated by the fact that the dissipation process is also important in the disk turbulence, we have investigated evolution of magnetic reconnection in differentially rotating system using the hybrid code as well. These are described in Chapters 3 and 4. In Chapter 3 we investigated the evolution of magnetic reconnection in the meridional plane of the disk. The initial magnetic field is aligned to the axis of rotation. Coupled with MRI, the magnetic reconnection showed a asymmetric structure during its evolution. At the same time, efficient reproduction of equatorial component of magnetic field is observed which is essential for Maxwell stress in the turbulence. We consider that the magnetic reconnection coupled with MRI contributes to efficient transportation of angular momentum.

In Chapter 4, we investigated evolution of magnetic reconnection in the equatorial

plane of the disk. The initial magnetic field was aligned to the azimuthal direction of the disk in this simulation. Since we assume a local structure in the disk, we have adopted so-called "open shearing periodic boundary condition" which is commonly used in the MHD calculation of differentially rotating system. We have also observed asymmetric evolution of magnetic reconnection in this plane basically due to the coupling of the outflow with the Coriolis force. By assuming periodicity, the evolution of the reconnection was affected by another reconnection site which is assumed to exist outside the actual simulation domain. Together with the shear motion, this effect gave an enhancement on the reconnection rate with a certain rotational parameter. We consider that this can be one of the fundamental processes in the accretion disk turbulence.

The present results imply existence of an efficient angular momentum transport in a collisionless accretion disk. The method we have established in the present studies would be also an important step for the further 3 dimensional simulation of the collisionless accretion disks.