論文の内容の要旨

Mechanism of Angular Momentum Transport in Collisional and Collisionless Accretion Disks

（衝突性および無衝突性の降着円盤における
角運動量輸送メカニズムに関する研究）

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This thesis explores anomalous transport mechanism of angular momentum via magnetohydrodynamic (MHD) turbulence driven by magnetorotational instabilities (MRIs) in accretion disks.　To trigger mass accretion onto a central compact object and resultant release of gravitational binding energy, which is believed to be an energy source for a wide variety of astrophysical phenomena, the angular momentum of the gas must be transported outwardly; otherwise the matter keeps to rotate around the central object by the strong centrifugal barrier.　However, it is known that the classical Spitzer-type viscosity carried by Coulomb collision provides a merely much smaller transport efficiency than an observationally constrained estimate.　While Shakura & Sunyaev (1973) successfully advanced accretion disk theories by introducing the well-known α-viscosity, which parameterizes the anomalous turbulent viscosity, the origin of the turbulence sustained in an accretion disk had been unknown for a long time.　Since Balbus & Hawley (1991) indicated astrophysical importance of the MRI as a strong driver of MHD turbulence, a number of authors have investigated the nature of the MRI intensively, mainly by non-linear MHD simulations.　We still, however, suffer from discrepancy between transport efficiencies estimated from observations and MHD

simulations. In this thesis, the generation of MHD turbulence is discussed by numerical simulations to seek for mechanisms which can further enhance the angular momentum transport. In particular, collisional and collisionless accretion disks are investigated separately.

In chapter 2, we focus on a *collisional* accretion disk, where the standard MHD approximation is applicable. Since a toroidal magnetic field becomes dominant through the so-called Ω-dynamo commonly in a differentially rotating system, it is of importance to investigate local behavior of the gas threaded by external toroidal magnetic flux. While the conventional MRI mode can grow from the seed toroidal field only for essentially vertically propagating waves, we have found that unstable eigenmodes completely confined within an equatorial plane can be present and drive MHD turbulence if the background toroidal flux has radial non-uniformity. This instability is termed a magneto-gradient driven instability (MGDI). It can provide sufficiently large α-viscosity mainly contributed by the Maxwell stress when the imposed toroidal flux is comparable to the saturation amplitude of three-dimensional local MRIs. The MGDI may work as a new possible path to drive MHD turbulence in accretion disks in a complementary manner with the toroidal MRI modes rather than in a competitive manner, and may play a role of significance in transport process by coupling with magnetic reconnection occurring along the equatorial plane.

In contrast, chapters 3 and 4 are devoted to turbulent transport in *collisionless* accretion disks, where the gas is so dilute that the mean free path of charged particles exceeds the scale size of an accretion disk. In this regime, the standard MHD approximation is no longer valid, and anisotropy in a velocity distribution function plays an important role to transport the angular momentum. Chapter 3 is designed to construct a new numerical framework to deal with this anisotropy precisely, which is interpreted as an anisotropic pressure tensor in a fluid-based model, by extending the classical double adiabatic approximation. By combination of the second-order moment of the Vlasov equation and a gyrotropization model for the pressure tensor, we have successfully developed a new kinetic, scale-free MHD model. In particular, the natural assumption that the gyrotropization rate is proportional to a local magnetic field strength enables us to solve magnetized and unmagnetized regions seamlessly without any numerical difficulty, which cannot be accomplished by the classical model involving singularity at null points. While we apply this model particularly to the problem of accretion disks in this thesis, the application also includes other large-scale collisionless plasmas such as the Earth's magnetosphere and solar winds.

Chapter 4 works on the first approach to large-scale, collisionless disk simulations using the model developed in the previous chapter. Specifically, the local assumption is relaxed in the vertical direction. It yields a *stratified* shearing box model and involves the concept of the disk's scale height, which cannot be resolved by fully kinetic approaches such as particle-in-cell (PIC) and Vlasov simulations. We found that the resultant transport efficiency averaged over the whole simulation domain remains at the same level as that obtained in the standard MHD. The anisotropic stress, however, localizes near the mid-plane with relatively weak gravity and reaches a comparable value to the Maxwell stress, which is consistent with previous work without stratification. This localization indicates the strong dependence of angular momentum transport to the background disk structure when the stress by thermal pressure anisotropy cannot be neglected, and emphasizes the necessity of global simulations in the future, to which our scale-free kinetic MHD model could contribute significantly.

Another result of importance is an enhancement of the Maxwell stress by taking a gyrotropization rate close to a dynamical time scale. Since this parameter is proportional to the magnetic field, a finite non-gyrotropy remains selectively in the vicinity of current sheets, where magnetic reconnection takes place. Our result implies that this non-gyrotropy tends to suppress the magnetic reconnection, which is qualitatively consistent with the test problem of one-dimensional reconnection provided in chapter 3. This suppression effect by non-gyrotropy suggests a mechanism to enhance the angular momentum transport in a different way from the assertion by Hoshino (2013), where the suppression of the magnetic reconnection was explained by parallel pressure enhancement by reconnection itself and only the role of gyrotropic anisotropy was taken into account. While we have to take care of the difference if the suppression mechanisms in PIC and the present kinetic model, this thesis certainly contributes to fill the significant gap between the fully kinetic approach and the existing fluid models, and sheds new light on theoretical understanding of the collisionless accretion disks.