論文の内容の要旨

Studies on development of three-dimensional magnetohydrodynamic turbulence reconnection
（三次元磁気流体乱流リコネクションの発展の研究）

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Magnetic reconnection is considered to be one of the most important fundamental processes due to its wide application. It converts ubiquitously existing magnetic energy into heating and accelerating plasma thus explains various astronomical events that relate to the efficient energy release. Numerous works that tried to solve the fast reconnection problems started from more than 50 years ago. However, there still remains a big issue that how the reconnection is accelerated to reach the fast energy output shown by the observations. In this dissertation, we executed numerical simulations of a current sheet with a finite guide field to understand the basic physics for reconnection inside a self-generated turbulent state.

Since the coexistence of multiple tearing layers was found in many numerical studies for a current sheet with non-zero guide field under random perturbation, the coupling between these layers might lead to a solution for fast reconnection. So first in Chap.2, we applied a pair of rotational-symmetric eigenmodes of tearing instability to understand the local mechanism of the coupling. We found that the coupling, namely the inflow-outflow coupling between diffusion regions that are not aligned with each other, increases the inflow as well as the local reconnection rate from the coupling side and triggers secondary tearing instability in the original diffusion regions.

In Chap.3, the consequences of the initial inflow-outflow coupling were examined both in the local and the global scales. With the partition of the diffusion region, a vent is open across the sheet that magnetic fields are ejected out to collide with the free field lines. The collision creates new diffusion regions outwardly. In the global view, the new diffusion regions form new reconnection layers that correspond to new energy modes, which have larger wavenumbers along the global guide field direction than the original modes. The creation of the new energy modes come from the nonlinear coupling of initial modes with the higher order harmonics of their counterparts. These new reconnection layers are close to the asymptotic magnetic fields, so they transport free energy into the turbulent sheet. Meanwhile, the old and new reconnection layers also build up inflow-outflow coupling across the sheet. It is found that the global reconnection rate increases.

In order to generalize our sheet-crossing coupling model, we re-examined the reconnection in the current sheet under random perturbation in Chap.4. As many tearing layers emerge together, they build up inflow-outflow coupling across the current sheet, while activating new energy modes outwardly. As the overall reconnection rate increases, the same story as the eigenmodes coupling simulation is retrieved.

We made a parameter survey on the layer distance to check the dependence of the inflow-outflow coupling model, as well as the nonlinear coupling that produces new energy modes in Chap.5. We found that when two layers are far apart, no coupling is built that each layer grows independently. When two layers are close, they efficiently build up inflow-outflow coupling and cascade the energy into energy modes with larger wavenumbers thus follow the sheet-crossing coupling picture. On the other hand, decreasing the global guide field will sufficiently shrink the distance between tearing layers. We thus also tested a simulation with a very weak guide field and found that the coupling is broken soon and substituted by a series of transient and local reconnection.

In Chap.6, we summarized our results first and discussed several different issues. We compared our reconnection rate with other measurements and found that the reconnection in our system can be as fast as the other spontaneous 3D reconnection simulations. As the bi-directional flow pattern is often observed in the astronomical events, we examine the interaction between 2D and 3D modes. We notice that even in the environment dominated by 3D modes, 2D modes can grow and coalesce into longer 2D modes that produce global bi-directional flow and large 2D flux tube. In addition, the contribution of our results to the turbulence reconnection studies and the possible extension to the particle regime were discussed. Future prospects were presented that many works can be done, such as the model dependence on the diffusivity, the boundary condition and the sheet structure, to make a wholesome theory.

In conclusion, we have developed a well-defined model on the fast 3D reconnection. We followed the development of the diffusion regions and found that the universal existing coupling between tearing layers across the whole current sheet is the essential part in the acceleration of the global reconnection. The coupling does not only increase the local reconnection for each reconnection layer but also produces the new reconnection layers that expand further into the magnetic reservoir where free energy is provided.