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# 論文内容の要旨

Magnetic reconnection process has been investigated over half a century. Still, some problems remain unsolved. The typical one is the onset problem, namely, how fast reconnection is initiated. Another important issue is how huge magnetic energy is converted to plasma energies in a short time scale.

Collisionless reconnection sets in when the current sheet is compressed as thin as ion kinetic scale by the external driving sources. After experiencing some transient phase the system can relax to a steady state in which reconnection rate balances the inflow rate of magnetic flux from the external region, and then a new equilibrium state is realized there through kinetic processes. Accordingly, driven reconnection model is applied to study physical processes of collisionless reconnection in a steady state in this thesis.

The research focus of this thesis is on the electron force balance in the electron dissipation region (EDR) where electron frozen-in condition is broken due to microscopic electron kinetic effect, and how energy conversion process takes place there, especially from magnetic energy to that of electrons, in steady collisionless driven reconnection.

The simulation domain is implemented on 2D and 3D rectangular open systems, and a one-dimensional Harris equilibrium is employed as an initial condition. Plasma inflow enters the simulation domain in y direction and the outflow leaves it in x direction in our coordinate system. In order to supply plasma inflow into the system and initiate reconnection, a driving electric field, which is stronger within the input window around $x = 0$ at initial stage, is imposed in z direction at the upstream boundary. Plasma outflow goes through the downstream boundary at $x = \pm x_b$, which is open for plasma particles and electromagnetic fields. In the 3D simulation case, the boundary conditions at $z = \pm z_b$ along the z axis are periodic. The following summary focuses mainly on the physical processes of steady reconnection based on the 3D simulation results.

It is found that a dissipation region with an enhanced electron current density extends from the reconnection point toward the downstream region, and a long thin EDR with dual structure is formed in a steady state. We show that the force balance in the direction of the reconnection electric field (the z direction) is quite different from that in the upstream direction (the y direction) in the EDR.

In the z direction, the Lorentz force balances the electric force just outside the EDR, and then decreases rapidly inside the EDR and vanishes at the reconnection point. The electron inertia term has a local peak around the electron skin depth, but it is canceled out by the electron pressure tensor term. Only pressure tensor term sustains the electric field at the reconnection point, i.e., reconnection electric field.

Because the driving electric field works mainly on magnetized electrons inside ion dissipation region and pushes them into the EDR, strong electrostatic field is generated through the charge separation. Thus, a new force balance state is realized in the upstream direction in the steady state. Although the pressure gradient force balances the Lorentz force in the Harris equilibrium, the electrostatic force balances the Lorentz force in the y direction in the new equilibrium state.

The energy conversion process inside the EDR is also studied intensively. According to the force balance in the upstream direction it is expected that magnetic energy is effectively converted to electron kinetic or thermal energy in a short time scale since only electron dynamics is dominant there.

We show that spatial variation of electron kinetic energies in the downstream direction is quite different from that in the upstream direction, which is deeply related to the dual structure of the EDR along the downstream direction. Electron inflow kinetic energy drops quickly as electrons come into the EDR in the upstream direction, while only z component of electron kinetic energy increases there through the electron acceleration by strong reconnection electric field in the EDR.

In the downstream direction, z component of electron kinetic energy decreases as they move away from the reconnection point, and it finally drops to a constant at the edge of the inner structure of the EDR. On the other hand, outflow component of electron kinetic energy increases and reaches its maximum around the edge of the inner structure of the EDR. It is also found that total electron kinetic energy is almost conserved in the inner structure region of the EDR, and thus the electron kinetic energy is converted from the z component to its outflow component by the Lorentz force.

We have clarified two important physical processes controlled by electron dynamics in steady collisionless driven reconnection, i.e., the relaxation into a new equilibrium state in upstream direction and effective conversion from magnetic energy to electron one in the EDR. Electron dynamics manifests itself in two aspects; the first is that continuous in-place electron inflow enhances strong electrostatic field, and the second is that current density is mainly sustained by z directed electron motion accelerated by reconnection electric field. Thus, the new force balance between electrostatic force and Lorentz force associated with enhanced current density is realized in the steady state. Furthermore, strong electron current density provides a path to convert magnetic energy to electron energy in the EDR through the interaction between particles and electric field.

# 論文の審査結果の要旨

磁気リコネクションは、太陽コロナや地球磁気圏等の宇宙プラズマ、核融合や自己組織化現象の研究を目的とする実験室プラズマで観測される普遍的な物理現象であり、高温無衝突プラズマにおいて短時間スケールで起こる磁気エネルギー散逸の物理機構等、磁気流体力学(MHD)モデルでは説明できない未解明の問題を含んでいる。本学位論文は、２次元および３次元電磁粒子シミュレーションにより、外部駆動源が存在する無衝突プラズマ中で発生する磁気リコネクションにおける電子ダイナミクスの役割を明らかにしたものである。

本研究で用いられた電磁粒子シミュレーションモデルは、プラズマが系の境界から流入・流出できる開放系境界条件を採用し、反平行磁力線を伴う初期平衡分布（ハリス平衡）に上流側から外部駆動電場によるプラズマ流を与えることにより、駆動型無衝突磁気リコネクションを実現させている。このモデルを用いて、長時間シミュレーションを実行することにより、電子・イオン流速度、電場、磁場、電流の空間分布や磁束のリコネクション率等の物理量が時間に依らず一定となる定常状態を得ることができる。本研究では、定常状態における運動量輸送やエネルギー変換過程に関する綿密な解析を行い、２次元と３次元シミュレーションに共通する主な結果として以下の項目１－４を、３次元効果に関する結果として項目５を得ている。

１）磁気リコネクション点近傍では、電子慣性効果、電子圧力テンソル効果により、磁力線への電子流体の凍結条件が破られる電子散逸領域が形成され、急峻な電子電流分布が生ずる。

２）リコネクション点の上流側から電子散逸領域へ向かう方向に沿って、イオンと電子の荷電分離により静電場が形成され、電子電流によるローレンツ力と静電場が釣り合う新たな力学平衡状態が実現する。生成された電荷密度は電子アルベン速度の二乗に比例する。

３）リコネクション点近傍では、電子の蛇行運動に由来する電子圧力テンソルが、平衡電流方向に平行な定常電場を維持する。

４）上流領域から運ばれてきた磁気エネルギーは、電子散逸領域において電子運動エネルギーへ変換される。リコネクション点近傍で主として電流を担っている電子の運動は、下流領域へ向かうにつれて、ローレンツ力により下流方向へ加速され、ピーク速度に達した後、減速し散逸領域外部へ流出していく。

５）３次元効果としてドリフトキンク不安定性が成長し電子圧力の低下をもたらすが、定常状態では、その影響は小さく、電子電流によるローレンツ力と静電場の釣り合いによる力学平衡は保たれ、磁気リコネクションにおける電子散逸領域の機能は維持される。

以上の研究成果は、電磁粒子シミュレーションに基づく電子スケールの物理過程の詳細な解析によって得られたものであり、リコネクション点上流部における静電場形成・力学平衡の発見と磁気エネルギー散逸・電子加速の物理機構の解明を新たにもたらし、外部プラズマ流により駆動される無衝突磁気リコネクションの研究の発展に大きく貢献するもの

と考えられる。よって、本審査委員会は、本論文が博士学位論文として十分価値があるものであると判定した。