I. PROGRESS REPORT

In the past three years, we have made significant progress in the study of magnetic field reconnection and plasma processes in the magnetosphere. Two Ph.D. theses and one Master thesis have been accomplished. A total of 43 research and review papers have been completed under the DOE support. A list of our publications completed during 1988-1991 is attached at the end of this section. In the following, we briefly describe some of the most important results obtained in the past three years.

A. Global Reconnection Configurations and Boundary Layer Structure
   at the Dayside Magnetopause

The global magnetic reconnection configurations at the dayside magnetopause are examined on the basis of global 2-D incompressible MHD simulations [41]. It is found that the global magnetic Reynolds number \( R_m \), the critical current density \( J_c \) for the resistivity enhancement, and the solar wind Alfvén Mach number \( M_{A\infty} \) are the most important parameters in determining the reconnection patterns at the dayside magnetopause. Magnetic reconnection patterns observed in the simulations include the quasi-steady single X line reconnection, the impulsive multiple X line reconnection, and the bursty single X line reconnection. Single X line reconnection tends to occur for a small \( R_m \) (< 100) while multiple X line reconnection takes place when \( R_m \) is large (> 200). A current-dependent resistivity and a large \( R_m \) lead to various multiple X line reconnection patterns at the dayside magnetopause, whereas a large \( M_{A\infty} \) results in magnetic reconnection in the high latitude region.

The structure of the reconnection layer at the dayside magnetopause is also studied based on 2-D MHD simulations [33]. It is found that in a symmetric configuration, the reconnection layer is bounded by a pair of slow shocks as predicted in Petschek's [1964] model. However, under asymmetric conditions typical of the dayside magnetopause, the reconnection layer is found to be bounded by an intermediate shock on the magnetosheath side and a weak slow shock on the magnetospheric side. Contact discontinuities and slow expansion waves can also be identified in the reconnection layer in some simulation cases. In the presence of a large \( \beta \), the ratio of plasma pressure to magnetic pressure, the slow shocks or the intermediate shocks in the reconnection layer become weaker. Two papers [33, 41] have been completed on this topic.

B. Collisionless Magnetic Reconnection at the Dayside Magnetopause

Collisionless magnetic reconnection at the Earth's dayside magnetopause is studied on the basis of comprehensive particle simulations. A two-and-one-half-dimensional \((2\frac{1}{2}-D)\) electromagnetic
particle simulation model with a driven inflow boundary and an open outflow boundary has been developed for the present study. The major findings are as follows. (1) The simulations exhibit both quasi-steady single X line reconnection (SXR) and intermittent multiple X line reconnection (MXR). The MXR process is characterized by repeated formation and convection of magnetic islands. (2) Particle acceleration in the reconnection process results in a power law energy spectrum of \( f(E) \sim E^{-4} \) for energetic ions with \( E > 40 \) keV and energetic electrons with \( E > 3 \) keV, where \( E \) is the particle energy. (3) Field-aligned particle heat fluxes and intense plasma waves associated with the collisionless magnetic reconnection process are also observed. Typical power spectra of fluctuating magnetic and electric fields are found to be \( P_B \sim f^{-3.8} \) and \( P_E \sim f^{-1.8} \), respectively, where \( f \) is the wave frequency. (4) When applied to the dayside magnetopause, the simulation results show that the MXR process tends to generate a simultaneous magnetic field perturbation on both sides of the dayside magnetopause, resembling the observed features of two-regime flux transfer events (FTEs). (5) An intrusion of magnetosheath plasma bulges into the magnetosphere due to the formation of magnetic islands may lead to the layered structures observed in magnetospheric FTEs. One Ph.D. thesis [32] and three papers [23, 31, 43] have been completed or published on this topic.

C. Chaos and Ion Heating in Slow Shocks

Our 1-D hybrid simulations of slow shocks with a subsonic upstream incident speed show that the critical intermediate Mach number, \( M_c \), depends on the shock normal angle \( (\theta_{n,B}) \) and the upstream plasma beta \( (\beta_1) \). Based on the simulation results, we proposed an ion heating mechanism of slow shocks, which is associated with the chaotic motion of particles in the downstream rotational wave field [38]. Our study indicates that the nonlinear interaction between the particles and the downstream wave field may result in the chaotic motion of particles and the damping of waves. The criteria obtained from our theory for the occurrence of highly chaotic particle motion are found to be consistent with our simulation results of slow shocks. Two papers [19, 38] have been completed on this topic.

D. A Nonlinear Model for the Fast Steady-State Magnetic Reconnection

A new theory for nonlinear fast steady-state magnetic reconnection was proposed [42]. The inflow region possesses highly curved magnetic field lines, which differs from that in the classical model of Petschek [1964]. A separatrix jet of plasma is ejected from the central diffusion region along the magnetic separatrix. Two types of outflow were studied. The simplest one possesses a potential outflow magnetic field and the other contains weak standing shock waves attached to the ends of the diffusion region. Across the separatrix jet, the outflow can be either slowed down
by the fast-mode shocks or speeded up by the slow-mode shocks, depending on the downstream boundary conditions. Our model is an important step in the theoretical study of the reconnection process. One paper [42] on this topic has been published and another simulation paper is in the preparation stage.

E. Formation of Frayed Magnetic Ropes in 3-D MHD Simulations of Magnetic Reconnections

The driven magnetic reconnection processes at the dayside magnetopause were studied on the basis of two-dimensional (2-D) and three-dimensional (3-D) magnetohydrodynamics (MHD) simulations. In the 2-D simulations, the steady-state fast magnetic reconnection with small separatrix angles is obtained when the given resistivity is nonuniform [40]. For a uniform resistivity model, it is found that no steady-state reconnection configuration can be obtained. In the 3-D MHD simulations, frayed-end magnetic flux ropes are formed during the dayside magnetic reconnection process. Strong flux rope-aligned plasma flows are observed [22, 25]. Simulations of the driven reconnection process also indicate that the focusing of the Poynting flux has an important effect on the onset of reconnection and the location of reconnection sites. Magnetic reconnection tends to take place in the region, which is near the focus of the Poynting vector imposed at the boundary. In the Earth's magnetosphere, the boundary conditions at the magnetopause determine the reconnection site in the magnetotail plasma sheet. In the solar atmosphere, the focusing of the Poynting vector imposed at the photospheric boundary through the field line motions may lead to the prominence eruptions. Altogether, one Ph.D. thesis [13] and seven research and review papers [15, 22, 25, 33, 34, 35, 40] have been completed on this topic. Another paper [46] is in preparation.

F. Different FTE Signatures Generated in Different Reconnection Models

FTE signatures generated by the bursty single X line reconnection (BSXR) and intermittent multiple X line reconnection (MXR) processes are examined based on 2-D compressible MHD simulations [39]. It is found that the FTE magnetic signatures are not exhibited on the magnetospheric side if the FTEs are due to the BSXR process and $B_m/B_s \geq 1.7$, where $B_m$ and $B_s$ are the magnetic field strength in the magnetosphere and in the magnetosheath, respectively. On the other hand, the bipolar FTE signatures can be detected on both the magnetosphere and magnetosheath sides if the FTEs are caused by the MXR process and $B_m/B_s \leq 2.6$. When $B_m/B_s > 2.6$, the bipolar FTE signatures in the magnetosphere site become too small to be detected even if magnetic islands are formed during the MXR process. Furthermore, for $B_m/B_s > 1$, the region for the detection of FTE signatures in the magnetospheric side is
smaller than that in the magnetosheath side. Since at the dayside magnetopause the typical value of $B_m/B_s$ is between 1 and 3, the simulation results indicate that it is likely for more FTE signatures to be detected in the magnetosheath side than in the magnetosphere. One paper [39] has been published on this topic.

G. Slow-Mode Structures in Front of Dayside Magnetopause

The interplanetary magnetic field (IMF) can pile up in front of the dayside magnetopause, leading to the formation of a plasma depletion layer. Recent observations show that in some satellite crossings of the magnetopause, as the solar wind approaches the dayside magnetopause, plasma density increases to reach a maximum value before it decreases in the depletion layer, resulting in the formation of a slow-mode structure in front of the dayside magnetopause. The slow-mode structure in front of the dayside magnetopause was studied with 2-D incompressible MHD simulations. It is found that slow-mode structures similar to the observations can be formed when the IMF has a $B_z$ component. When the $B_z$ component of the IMF is present, the bending of magnetic field lines in front of the magnetopause leads to the formation of the slow-mode structures. One paper on this topic [37] has been published in *Geophysical Research Letters.*

H. Vortex Structures in the Low-Latitude Boundary Layer and Auroral Bright Spots in the Polar Ionosphere

The lower-latitude boundary layer (LLBL) vortex structures were studied on the basis of 2-D MHD simulations, including ionospheric effects. In the presence of a normal diffusion flux and the mass transport at the magnetopause, it is found that the Kelvin-Helmholtz instability may lead to the formation of vortex flow and density structures in the low-latitude boundary layer. When the ionospheric effects are included, it is found that the ionospheric conductivity provides a dissipation, which may lead to the decay of the vortices formed in the low-latitude boundary layer. Several enhanced conductivity regions which are associated with the boundary layer vortices and the upward field-aligned current filaments can be found along the post-noon auroral oval. These enhanced conductivity regions may account for the bright auroral spots observed in dayside auroras. Two papers [24, 29] have been completed and published on this topic.

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I. A List of the Theses and Papers Supported by DOE Grant DE-FG06-86ER 13530


