3-2 Generation of Convection in the Magnetosphere-Ionosphere Coupling System

TANAKA Takashi

Based on the magnetosphere-ionosphere (M-I) coupling scheme, convection as a complex (compound) system is considered including the generation of plasma population regimes in the magnetosphere. To guarantee the self-consistency, the MHD simulation is adopted to analyze the problem. In these considerations, primary elements that must be set to a self-consistent configuration are convection flows in the magnetosphere and the ionosphere, filed aligned current (FAC) systems, ionospheric currents, energy conversion processes, and plasma pressure. Then, global current systems coupled with plasma population regimes are derived from the magnetohydrodynamic (MHD) force balance controlling the convection. The magnetospheric model derived from this consideration is the closed magnetosphere with open cusp. Based on the convection model proposed in this paper, a suggestion is given for the substorm models in the next decade that they must develop from a modular model to a globally self-consistent model.

Keywords
Convection, Field-aligned current, Dynamo, Substorm, State transition

1 Introduction

Passing the Parker's singular point, most of the internal energy of the solar wind is converted into kinetic energy, and from there on, kinetic energy becomes dominant in the solar wind. The primary process in the formation of the magnetosphere is the confinement of the Earth's magnetic field by this single-sided dynamic pressure from the solar wind. In ideal magnetohydrodynamic (MHD) processes, the solar wind plasma and magnetospheric plasma (if present) would not mix, resulting in a quiet magnetosphere. In such a case, the magnetopause would represent a tangential discontinuity. However, in reality, the solar wind plasma penetrates into the magnetosphere through non-ideal MHD processes such as reconnection, filling the magnetosphere with plasma. Furthermore, the penetration of momentum and energy induces large-scale convection in the magnetospheric plasma, involving in the ionospheric plasma as well. Auroras and radiation belts are generated as a part of this convection. The convection also generates electric currents in accordance with the laws of MHD, creating a large-scale current system in the magnetosphere ionosphere system. The various changes in the magnetic field observed on ground or in the magnetosphere are manifestations of this current system (See Chapter 4).

The penetrated plasma is not uniformly distributed in the magnetosphere, but tends to accumulate in specific regions such as cusps, the low-latitude boundary layer (LLBL), the mantle, plasma sheets, and in ring currents. This magnetospheric plasma structure can be understood to some extent through the equilibrium configuration based on single-particle descriptions and local MHD. Furthermore, since these magnetospheric plasma structures correspond to the current in each region, the magnetic field structure of the magnetosphere can be explained approximately in terms of currents derived from single-particle descriptions, such as magnetization current and drift current (See Chapter 1).

It is apparent that the plasma structure and current system are not independent of each other; on the contrary, they are inextricably linked. Moreover, they are closely connected to convection. However, to further relate plasma structure and current system with convection, the 3D self-consistent structure of the magnetosphere and ionosphere must be investigated. Although the self-consistent structure must not violate any laws of basic physics, the laws of basic physics alone cannot completely explain the interactions between the three components, since the interactions are dependent on topologies specific to the magnetospheric and ionospheric regions. Thus, simulation studies become essential for such examinations to make the difference clear between physics and the earth and planetary sciences.

It is well known that the concept of convection starts with *Dungey* (1961) and *Axford and Hines* (1961). Of the two, *Dungey* (1961) had wide appeal and is still adopted by many researchers as the basic concepts for many studies. The discovery of field-aligned currents (FAC) by *Iijima and Potemra* (1976) ought to have given new meaning to the concept of convection. However, it took an unexpectedly long time before this discovery was understood as the other manifestation of convection (*Iijima*, 2000). This was a result of a limited understanding of the magnetospheric closure process of FAC and uncertainties in its topology; this was in its contrast to the fairly advanced studies of ionospheric closure of FAC resulting in geomagnetic variations. Recent MHD simulations have reproduced the magnetospheric closure process of FAC (*Tanaka*, 1995) and revealed the relationship between convection and FAC, which has advanced our understanding of the interactions between plasma structure, current system, and convection. Understanding the structure of the convection system is now considered to be an essential element in the comprehension not only of disturbance phenomena such as substorms (*Akasofu*, 1964) and magnetic storms, but also of apparently unique phenomena such as sudden commencement (SC) and theta auroras.

2 Magnetosphere-Ionosphere Coupling in a Convection System

In a coupled system of the magnetosphere and ionosphere, magnetospheric convection proceeds involving the ionosphere; this convection becomes the most fundamental process in transferring the free energy of disturbances in the magnetosphere-ionosphere system. When examining this system, it is necessary to recognize which is more essential, **BV** (magnetic field & velocity) or **EJ** (electric field & current), as basic parameters to describe the plasma dynamics. In studying magnetospheric physics focusing on convection, which is a fluid-dynamic phenomenon, the **BV** paradigm should be selected, since fluid dynamic descriptions using **BV** as basic parameters automatically ensure dynamical self-consistency. In this case, distortions are created in the magnetic field as it is carried along with the fluid, which in turn induces currents to affect the fluid motion. Therefore, in this paradigm, J is the result of changes in B (*Parker*, 2000).

In contrast to the **BV** paradigm of the fluid-dynamic model, in particle modeling, motions of particles generate electric currents and fields, which then induce changes in the magnetic field that in turn controls particle motion. Therefore, **EJ** are more basic parameters (*Lui*, 2000), and J becomes the cause of changes in the magnetic field. If current disruption and reconnection are assumed to be the basic processes in magnetospheric disturbances, the **EJ** paradigm should be selected to examine the physics of the magnetosphere, since they cannot be incorporated into the **BV** paradigm. However, at present, some difficulties remain in satisfying the requirements of global self-consistency in the **EJ** paradigm.

2.1 The Slab Model and the Generation of a Global Current System

As the basis for understanding how magnetosphere-ionosphere coupling constructs a convection system, let us consider the slab model (Fig.1). In Fig.1, M, F, and E represent the magnetosphere, ionospheric F layer, and ionospheric E layer, respectively. The entire system is coupled by a magnetic field. The figure represents a moment at which shear motion is generated in the M region and the front portion is just beginning to move. The slab model is a simple analogy, but it is well-suited to explain why the generation of a global current system is unavoidable when the velocity (electric field) is projected from the magnetosphere onto the ionosphere. The magnetospheric convection transfers the magnetic field according to the frozen-in principle. However, if no ionospheric convection exists, growing distortions perturbations are generated in the magnetic field, generating magnetic tension that accelerates the ionosphere. In reaction, the magnetosphere is decelerated, and the convective motion is controlled. The

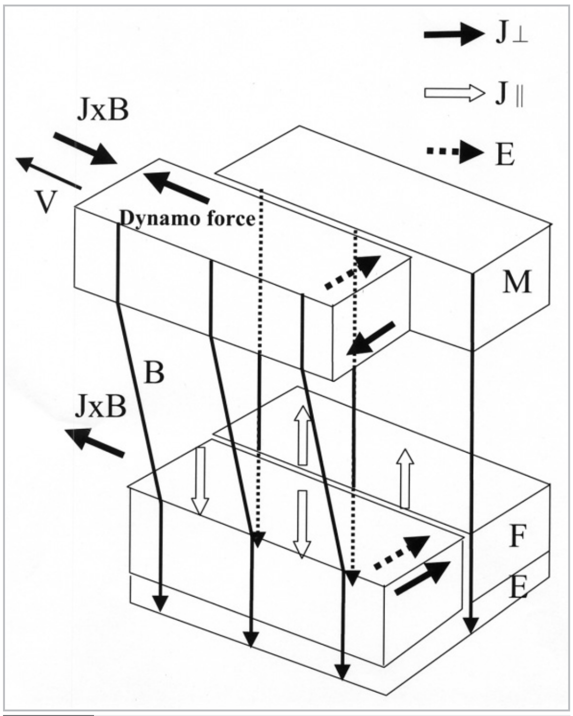

Fig.1 *Slab model of convection*

M, F, and E represent the magnetospheric domain, the ionospheric F layer, and the ionospheric E layer, respectively.

actual solution is the point at which this interaction is balanced. The characteristic of the slab model is that it considers convection within the **BV** paradigm. In this model, the electric current is a result of the distortions in the magnetic field, and is not the cause of changes in the magnetic field. Furthermore, the electric field is included in the scheme only when it is used for supplementary explanations. As a result, FAC, ionospheric current, and magnetospheric current form a closed circuit in this model.

In the **BV** paradigm, current is not a main parameter for the MHD process. However, the existence of the ionospheric E layer makes it difficult to exclude currents when discussing convection. As evident from the slab model, currents are continuous, and the FAC accompanies ionospheric closure on one hand and magnetospheric closure on the other. Therefore, it is essential to clarify these closure processes in discussing the mechanics of convection. For a stationary convection, there must be a force that counters the $\mathbf{J}\times\mathbf{B}$ force in the magnetosphere. The work performed by this force against the $\mathbf{J}\times\mathbf{B}$ force keeps $\mathbf{J}\cdot\mathbf{E}$ negative. This action is referred to as the dynamo. In this process as well, consideration of the current aids in understanding the mechanics of the magnetospheric convection. In the dynamo region, $\mathbf{V}$ and $\mathbf{J}\times\mathbf{B}$ must be anti-parallel. The force countering $\mathbf{J}\times\mathbf{B}$ (dynamo driver) determines the power of the dynamo, but the required force is dependent not only on the convection velocity $\mathbf{V}$ but also on the ionospheric conductivity Σ.

2.2 Current System and the Projection of Velocity and Electric Field

The explanation that magnetosphere-ionosphere coupling in a convection system is realized through the projection of the magnetospheric electric field onto the ionosphere may seem convincing. However, if the coupling is explained as a projection of velocity from the magnetosphere onto the ionosphere according to the frozen-in concept.

$$\mathbf{E} + \mathbf{V} \times \mathbf{B} = 0, \qquad (1)$$

then a simple question arises as to what forces acted in the system to produce such results. This reflects the question of whether to choose the **BV** or the **EJ** as the basic parameters of plasma. When E is used in a fluid-dynamic description such as convection, the equation of motion becomes hidden, turning attention away from mechanics as a balance of force. Such confusing perceptions frequently arise under the **EJ** paradigm, and so the **BV** paradigm is considered more appropriate in the discussion of magnetosphere-ionosphere coupling, as in the slab model. However, currents cannot be totally ignored, due to the presence of the ionospheric E layer. This is because MHD does not apply to the E layer; instead, an analogy to an electric circuit (**EJ** paradigm) is applied. Therefore, it is essential to include the effects of current in the discussion.

Sonnerup (1980) examined a convection model of velocity projection onto the ionosphere by generating FAC using viscous force for dynamo action. The topology of this model more closely resembles the actual magnetosphere than does the slab model, and is instructive in that it explains self-consistency between the magnetosphere and the ionosphere. However, the convection is not reconnection driven, and thus does not fully reproduce the actual state of the magnetospheric convection. The Rice Convection Model, which treats only the inner magnetosphere, generates FAC based on drift motion of particles caused by the electric field, and projects the convection onto the ionosphere (*Harel et al.*, 1981). Therefore, the Rice Convection Model falls under the **EJ** paradigm, although it assumes a boundary condition for E.

MHD simulations are required to generate FAC in a magnetospheric convection model that is closer to the actual state and to project the convection onto the ionosphere. However, there is a large gap in scale between the magnetosphere and the ionosphere. To overcome this gap and to project the convection onto the ionosphere numerically, MHD simulations using unstructured grids are being studied (*Tanaka*, 1995; *Siscoe et al.*, 2000; *Gombosi et al.*, 2000). The section below will mainly focus on the results of unstructured-grid MHD simulations.

3 Ionospheric Closure of FAC and Ionospheric Convection

The process of ionospheric closure of FAC is a classic problem in geomagnetism, and has been a subject of intense study since Birkeland (*Kamide et al.*, 1996; *Cowley*, 2000). When ionospheric convection is described using potential electrical field ϕ, 2-dimensional electrical conductivity tensor Σ, and FAC $J_{\parallel}$, then ionospheric closure can be expressed as

$$\nabla \bullet \Sigma \nabla \phi = J_{\parallel}, \qquad (2)$$

which essentially represents an energy loss

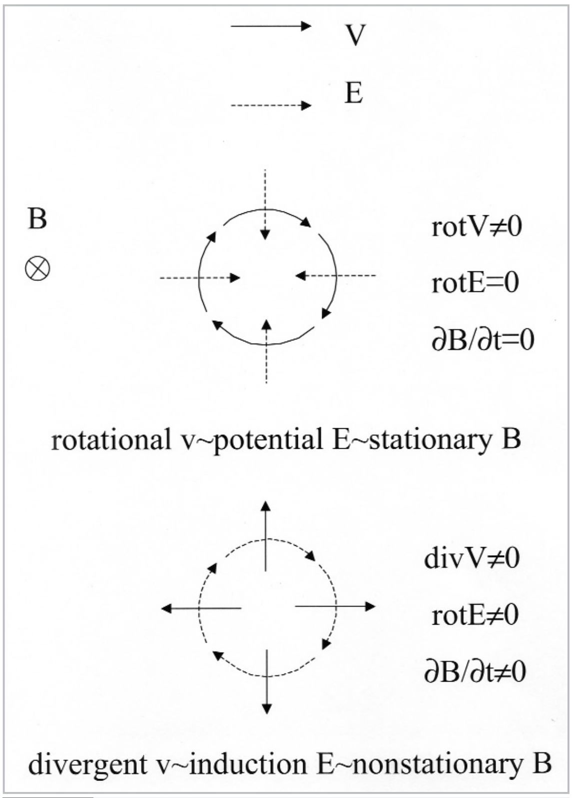

Fig.2 *Relationship between velocity and the electric field inside plasma*
The top and bottom panels are for rotational motion and divergent/convergent motions, respectively.

process. Using potential to express the electric field is equivalent to assuming that the magnetic field is stationary ($\partial \mathbf{B}/\partial t = 0$) and that the motions in the ionosphere are restricted only to eddy motion (div$\mathbf{V} = 0$). The top panel in Fig.2 illustrates the relationship for the above case. The bottom panel is provided for comparison with a case of inductive electric field. In the latter case, divergent and convergent motions are generated, and a stationary magnetic field cannot be maintained.

It is widely known that when Σ is constant, only the Pedersen current must be accounted for in current closure, since the Hall current is closed within the ionosphere. Since Σ is not constant due to EUV ionization and ionization by particle precipitation, the Hall current must also be considered in ionospheric closure. Furthermore, it is known that non-uniform Σ in the auroral oval results in Cowling conductivity, and this forms one of the central concepts geomagnetism: the electrojet.

The relationship between convection and FAC in ionospheric closure process can be approximated to a condition that FAC is present in the center of shear in the convection. This situation can be understood from the relationship between convection potential and FAC presented in Fig.3. The left panel in Fig.3 shows the case of uniform Σ and the right panel illustrates the case of non-uniform Σ caused by EUV ionization and ionization by particle precipitation. In these panels contours represent ϕ, and the color scale represents $J_\parallel$. When Σ is uniform, the region 1 current approximately corresponds to the shear created by the tailward flow in the polar caps and the sunward flow in the auroral oval, and region 2 current approximately corresponds to the shear created between sunward flow in the oval and the stationary region at lower latitudes (*Cowley*, 2000; *Tanaka*, 2001). However, when Σ is non-uniform, the relationship between convection shear and current is slightly displaced, because charge accumulation and resulting electrostatic field occur in the ionosphere in order to maintain current continuity. Thus, it can be seen that the projection of velocity (electric field) is not a one-way process from the magnetosphere to the ionosphere; it also works in the reverse direction.

4 Magnetospheric Closure of FAC

The magnetosphere has a complex topology, and the magnetospheric closure of FAC in

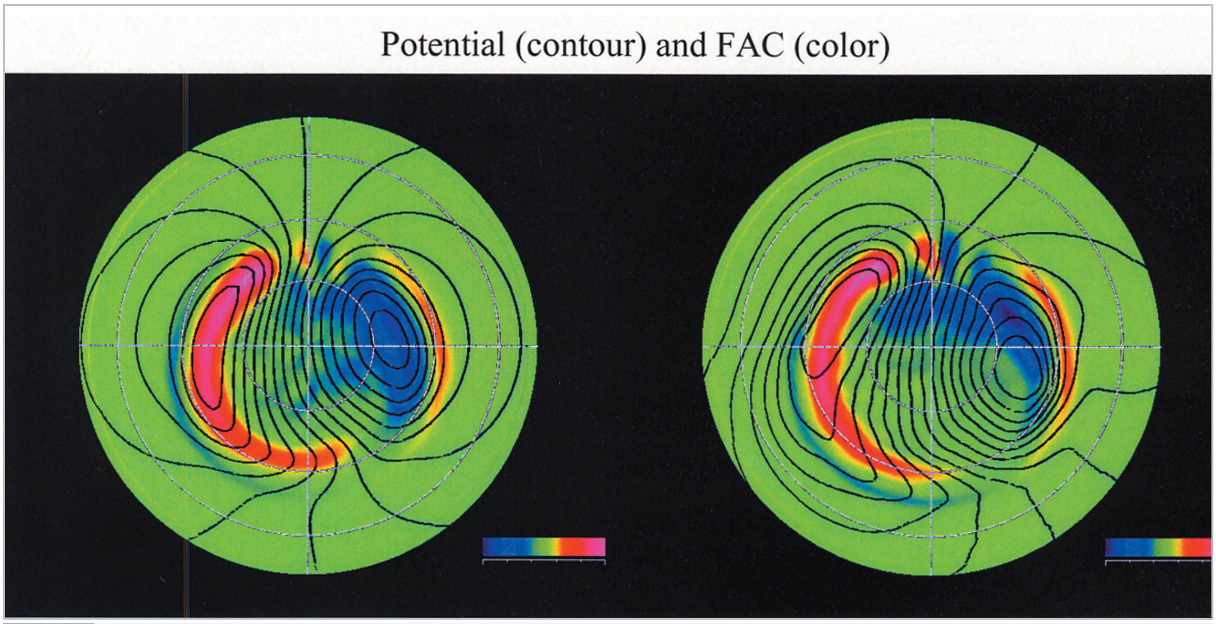

Fig.3 *Ionospheric potential and FAC*
FAC is represented by the color scale, and potential is represented by contours. The plots on the left and right are for uniform and non-uniform electric conductivity of the ionosphere, respectively.

the slab model is not realistic. However, the principle can still be similarly applied to the real magnetosphere. In the actual system, the magnetosphere is not necessarily incompressible, but near the ionosphere, there is a low-beta region that is considered to be incompressible. However, as in the slab model, the magnetospheric convection carries the magnetic field together with it according to the frozen-in concept, and then a kink structure will be produced at the boundary between the low-beta region, which is propagated through the low-beta region (Fig.4). This process represents a case of magnetosphere-ionosphere coupling by FAC similar to that seen in the slab model. In this process, charge accumulation by FAC occurs, decelerating convection, because it is positive at low potential regions and negative at high potential regions. Therefore, coupling with the dynamo is essential to drive convection against charge accumulation. These principles are similar to those of the slab model, and the driven convection must accompany the dynamo and FAC. Thus, the FAC path that connects the ionosphere with the dynamo must be examined first (*Stern*, 1983).

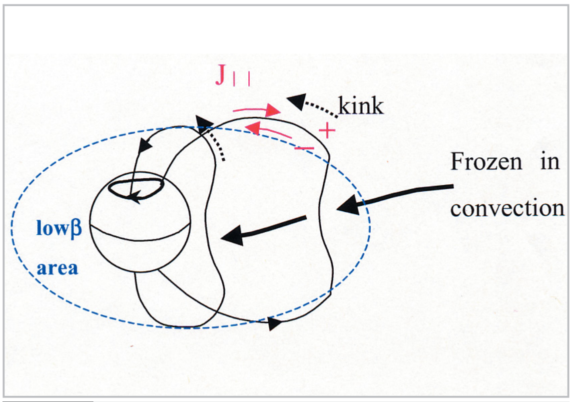

Fig.4 *Schematic diagram of magnetosphere-ionosphere coupling*
The dashed and solid arrows represent the directions of kink propagation and FAC, respectively.

4.1 Magnetospheric Convection and the Dynamo

It is clear from the above discussions that the dynamo must be included for magnetospheric closure of FAC. However, energy must be supplied to form the dynamo. In this case convection is steadily driven by the energy-supplying process incorporated into magnetospheric convection; this is the mechanism that supplies electromagnetic energy to the ionosphere. For this process, mechanical energy (kinetic or internal energy) must be converted into electromagnetic energy. However, to investigate this dynamo action in the actual magnetosphere, the closure path of FAC in the magnetosphere must first be identified.

In recent years, MHD simulations have been undertaken to calculate how FAC is closed in the magnetosphere (*Tanaka*, 1995; *Siscoe et al*., 2000). Fig.5 shows an example of the calculation for region 1 current closure in the magnetosphere. The region 1 current, which plays a central role in convection, closes at higher latitudes of the cusp. The FAC follows the magnetic field line in the low-beta region, but does not necessary do so at higher altitudes outside of the low-beta region (*Tanaka*, 1995). Studying the **J**•**E** distribution is effective in examining the closure process of the region 1 current at latitudes higher than the cusp. Fig.6 shows the **J**•**E** distribution at the 12-0 o'clock meridian and the equatorial planes. In this figure, the interplanetary magnetic field (IMF) has a southward orientation, corresponding to the substorm growth phase. At the bow shock, **J**•**E** is negative, indicating that the magnetic field is compressed by solar wind that has lost its kinetic energy according to deceleration from supersonic to subsonic velocity. At the magnetopause, **J**•**E** is positive, which corresponds to a condition in which energy is supplied to the plasma by magnetic tension resulting from the sharp bend in field lines at the reconnection.

In the region around the mantle and latitudes higher than the cusp, **J**•**E** is negative, and it can be seen from Fig.5 that this is the source region of the region 1 current. It can be observed from Fig.6 that the magnetic field lines in regions where **J**•**E** is intensely colored constitute the cusp (1) in both the magnetosphere and the ionosphere. Energy conversion

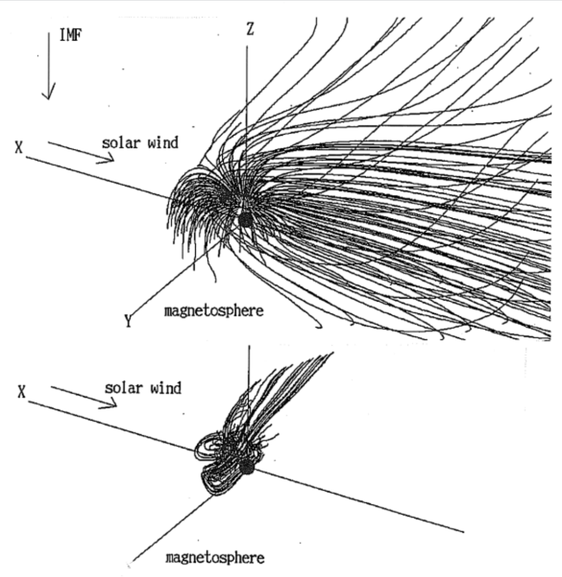

Fig.5 *Magnetic field (top) and region 1 electric current (bottom) of the magnetosphere shown for the 1/4 region of positive y and z values*

The conditions correspond to the growth phase.

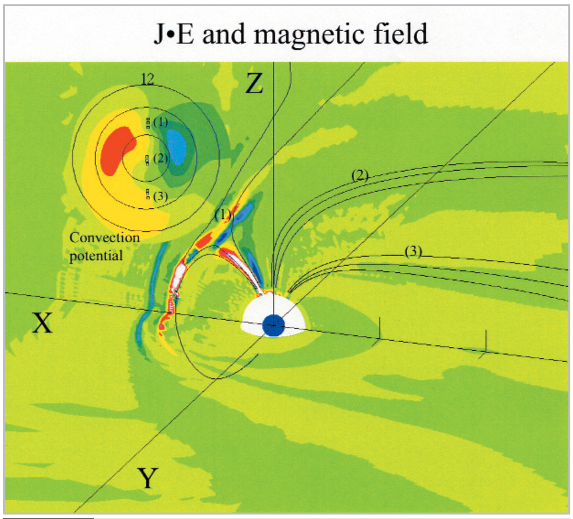

Fig.6 *Magnetic field and J•E distribution shown for the 12-0 o'clock meridian and equatorial planes*

The ionospheric electric potential is represented by the color scale, and the circles represent 60˚, 70˚, and 80˚ latitudes.

is not observed along the magnetic field line extending from the polar cap to the lobe (2). The primary factor in the formation of the magnetosphere is solar wind dynamic pressure. At this stage, the magnetosphere is closed. In Fig.5, the magnetosphere is open at the cusp due to reconnection, indicating that force is exerted at the cusp and that energy conversion takes place there. The entire magnetosphere does not open, as described in *Dungey*. Therefore, there is a clear distinction between the cusp and the polar cap.

On the other hand, region 2 current, reproduced by simulation, is closed at the inner edge of the plasma sheet (*Tanaka*, 1995). This is the topology of a partial ring current, and is consistent with the topology predicted in previous studies (*Cowley*, 2000). At the inner edge of the plasma sheet, current is perpendicular to the magnetic field, and it is converted into $J_{\|}$ in the region where ∇P is present in the longitudinal direction of the inner magnetosphere; it then flows into (or out of) the ionosphere. The dynamo of the region 2 current exists in this region, where ∇P is present in the longitudinal direction. In contrast, **J**·**E** is positive in the plasma sheet. FAC having this structure corresponds to that calculated in the Rice Model.

4.2 Energy Conversion by Convection

Let us re-investigate the force balance in the convection crossing the cusp and the polar cap (Fig.7). Let us assume here that the velocity inside the magnetosphere is small (the reason for this will be given later), and that

$$\mathbf{J} \times \mathbf{B} = \nabla P. \quad (3)$$

On the lower-latitude side of the cusp, convection flows from the low-pressure to the high-pressure side. Magnetic tension forces makes it possible for the convection to flow in the direction opposite the pressure gradient (electromagnetic pumping). The work here is done by the electromagnetic force on the plasma, and therefore, this can indeed be considered electromagnetic pumping. On the higher-latitude side of the cusp, this relationship is reversed and the plasma does the work and drives the dynamo. Thus, work dW done by the magnetic field is

$$dW = \mathbf{F} \cdot d\mathbf{s} = (\mathbf{J} \times \mathbf{B}) \cdot \mathbf{V} dt, \quad (4)$$

therefore, when convection **V** is parallel to

J × **B**, then work is done by the magnetic field, and pumping occurs with positive **J**•**E** is positive. In contrast, when convection **V** is anti-parallel to **J** × **B**, then work is done on the magnetic field, and the dynamo is realized at negative **J**•**E** (*Tanaka*, 2000a).

The dynamo may also be generated by the acceleration and deceleration of convection (Fig.8, top). In this case, **J** × **B** balances with dynamic pressure. However, the magnetospheric convection in this process contains a compressional component, making it difficult to realize self-consistent connection with low-beta shear motion generated by ionospheric FAC and ionospheric convection. As can be seen from the bottom panel in Fig.8, constant-velocity convection can more easily satisfy self-consistency throughout the entire system, because it contains no compressional component and connects smoothly with ionospheric convection. In this case, the presence of the

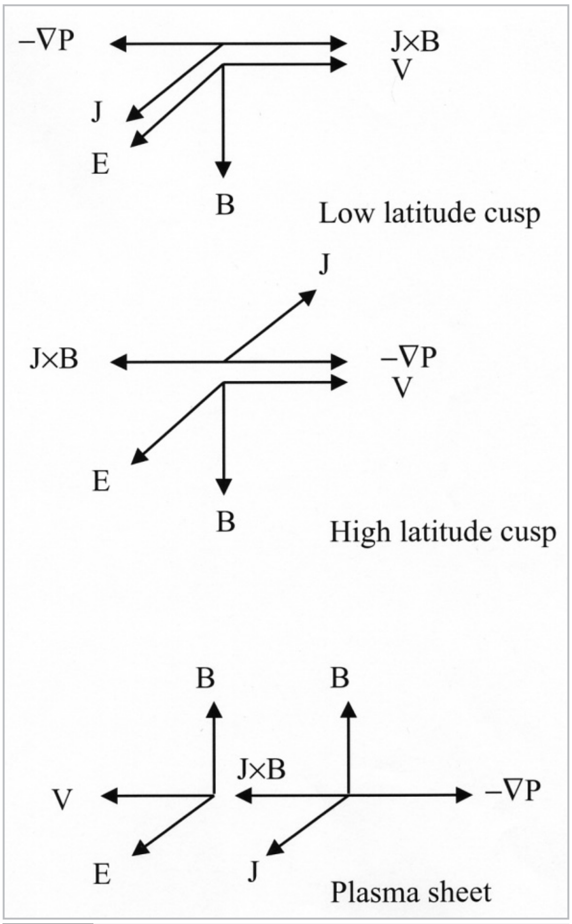

Fig.7 *Balance of forces at various positions in the magnetosphere*

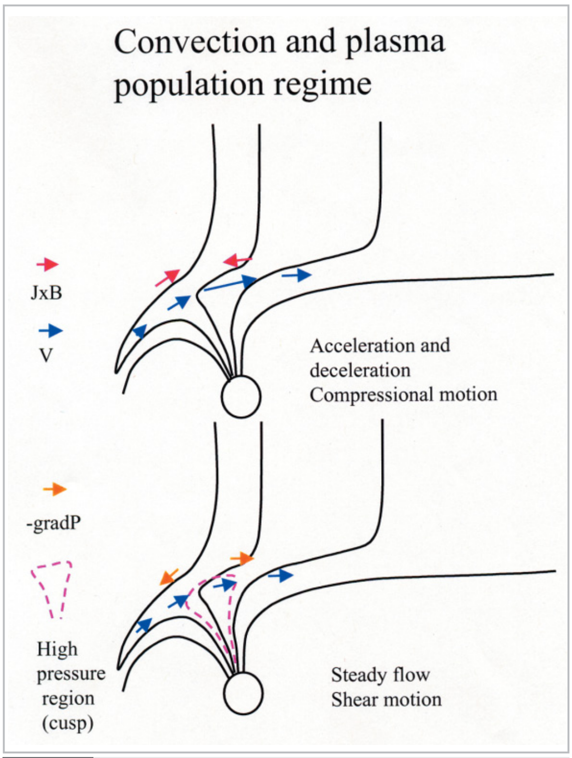

Fig.8 *Schematic diagrams showing the energy conversion process in the cusp*

The top panel represents a case in which kinetic energy predominates and the bottom panel represents one in which internal energy predominates.

cusp is essential for a dynamo driven by internal energy. To further confirm this theory, a comparison of internal energy and kinetic energy is presented in Fig.9. Generally, kinetic motion inside the magnetosphere is small, and the conversion of energy by acceleration and deceleration does not play a major role. This situation becomes a latent factor in the system, which leads to a change due to state transition; this point will be explained later in further detail.

By applying similar logic to the plasma sheet, it becomes clear that convection represents an energy conversion system. The relationship in Eq. (3) also holds in the plasma sheet, and the magnetic tension is in balance with the pressure gradient. Convection u is parallel to **J** × **B** and anti-parallel to $-\nabla P$, and electromagnetic energy is constantly being converted into mechanical energy. As a result, the entire plasma sheet acts like a pump; this structure causes internal energy to

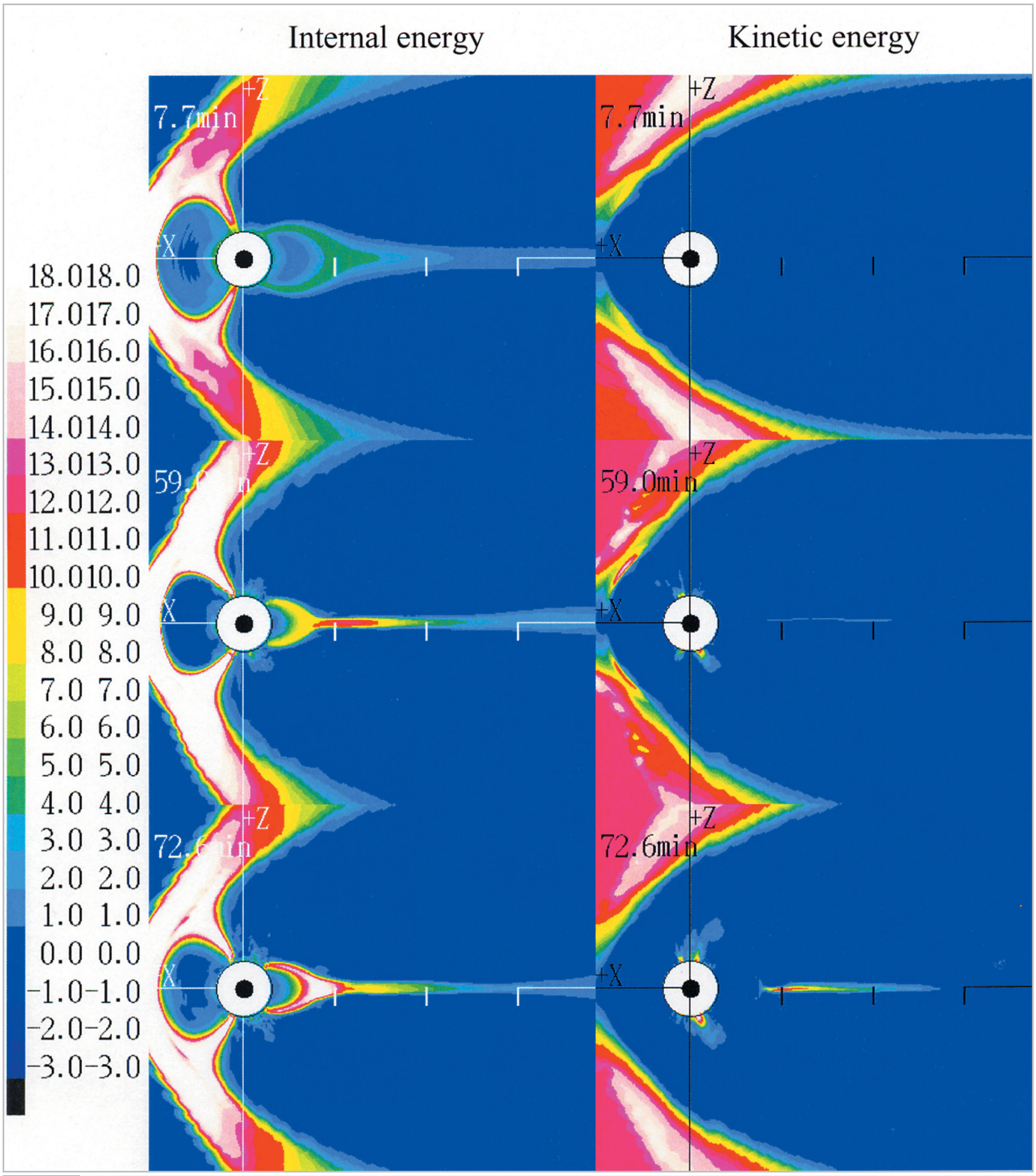

Fig.9 *Distributions of kinetic and internal energies in the magnetosphere for (from top to bottom) the quiet state, the substorm growth phase, and the substorm expansion phase*

accumulate constantly at the inner edge. Using this internal energy as the source, convection extending from the inner edge of the plasma sheet to the dayside drives the region 2 current. This convection **V** is anti-parallel to $\mathbf{J} \times \mathbf{B}$ and parallel to $-\nabla P$.

Where is the energy to drive the plasma sheet pump transported from? Clearly, it is from the θ current system in the magnetospheric tail. The energy driving the θ current system is exactly the same as that of the region 1 current, and is generated in the mantle. It can be said that the θ current system transports the electromagnetic energy generated in the mantle to the plasma sheet.

As evident from the above discussions, magnetospheric convection is an energy conversion system that converts solar wind energy into electromagnetic energy and successively converts it to internal energy, and again converts it back to electromagnetic energy, maintaining self-consistency on the whole.

4.3 Coupling Between Convection and Plasma Structure

In the magnetosphere physics discussed at present, the generation of a plasma region in the magnetosphere (including cusps and plasma sheets) is the result of localized mechanical balance and has no direct ties with global dynamics such as convection and the dynamo. The generation of plasma regions is simply a topological problem, and is not a dynamic one. However, in a system in which internal energy is dominant relative to kinetic energy and the dynamo is driven by internal energy, convection and the magnetospheric plasma region become coupled, and structures such as cusps and plasma sheets become dynamic. Without the cusps and plasma sheets, the convection system cannot achieve self-consistency. The cusps are essential to the generation of region 1 current and plasma sheets for region 2 currents.

Convection, current systems, and magnetospheric plasma regions are all coupled, and cannot be discussed independently. Fig.10 shows a composite system in which all three are self-consistent. Convection of the substorm growth phase driven by dayside reconnection, SC convection driven by compression, and convection at the onset of substorms accompanying dipolarization are all generated in this system, and although they have distinct topologies, they share a common principle in the realization of global self-consistency.

Convection is a phenomenon in a topological system. Earth and planetary sciences characteristically deal with topological systems, rather than with universal laws of physics in a flat space. A discovery in physics must be an explanation of a phenomenon based on universal principles, involving the reduction of the phenomenon to its basic elements. In contrast, given the significance of topology in earth and planetary sciences,

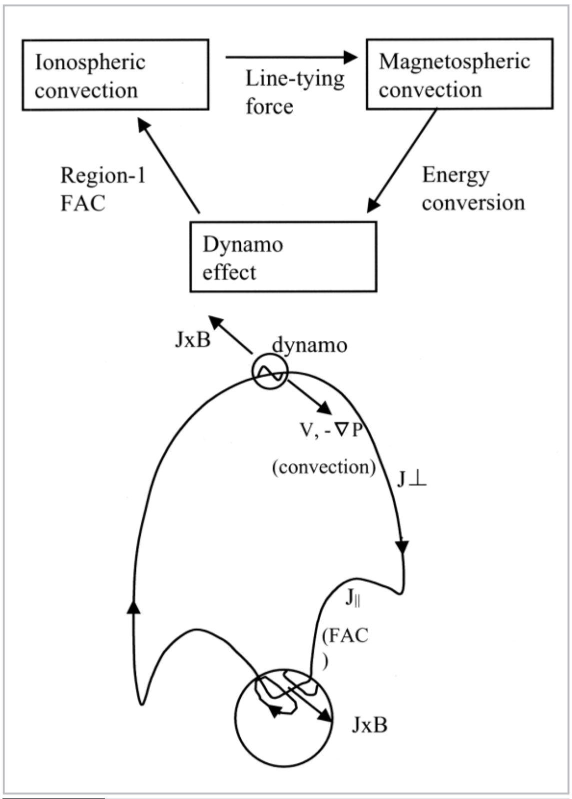

Fig.10 Schematic diagram of the composite system

phenomena cannot be reduced to their component parts without the loss of their essential characteristics. Earth and planetary sciences represent the physics of composite systems, which treat the systems as is, recognizing that topology of these systems is tied to self-consistency. Another way to define such a composite system is to refer to it as a system that allows state transitions.

5 Convection Structures under More General Conditions

Up to this point, the magnetosphere-ionosphere convection system has been discussed mainly assuming a due southward IMF. What are the characteristics of convection in a more general case? When dealing with magnetosphere-ionosphere disturbance phenomena such as substorms, an IMF oriented due south or north is generally assumed. However, such orientations rarely exist in nature. To allow for more generalized discussion, it is important to consider cases of an IMF with obliquely southward or northward orientations.

5.1 Obliquely Southward IMF

Rotation in the Y-Z plane of IMF has a significant effect on dayside reconnection that is the first phenomenon induced after contact with the magnetosphere. There are presently two types of structures proposed for dayside reconnection: antiparallel merging and component merging (*Crooker*, 1990). The results of MHD simulations support the former (*Ogino et al.*, 1986; *Tanaka*, 1999). Fig.11 shows an MHD simulation result of dayside reconnection during obliquely southward IMF. The broken lines represent reconnection lines. The reconnection lines are orthogonal to the IMF at a proper distance from the center, which is true in the case of component merging too. However, the lines converge at the north and south cusps near the Earth, and this structure is characteristic of antiparallel merging. The first significant feature in Fig.11 is the lack of bilateral symmetry of the closed magnetic field. This implies that not only IMF is distorted by draping immediately before reconnection, but also geomagnetic fields involved with the reconnection are also distorted (*Cowley*, 1973). This is normally referred to as the presence of a diffusion region.

Another peculiar structure can be seen in Fig.11. Relatively far from the center, IMF strucutures (such as 1, 2, 6, and 7) can reconnect on a one-to-one basis with the geomagnetic field. However, near the center, all of the IMF structures 3, 4, and 5 must reconnect with a single magnetic field line at the cusp. In other words, in the central region sandwiched between the north and south cusps, a dead zone of reconnection is produced, and all IMFs impinging on this dead zone are put to the cusp. To date there have been no studies investigating this structure in detail. This may be related to the FTE or to the unsteady dynamics of the cusp ionosphere.

The effect of oblique IMF, or *By*, is most evident in the structure of the ionospheric convection cell. This problem has been investigated using various methods, such as satellite, radar, and geomagnetic observations (*Heppner and Maynard*, 1987; *Weimer*, 1995; *Ruohoniemi and Greenwald*, 1996). Fig.12 shows the asymmetry of convection cells due to the *By* effect (*Tanaka*, 2001). The cell structure displays antisymmetric patterns with respect to the morning and evening sectors for *By*+ and *By*−, although the two are not perfectly mirror-symmetrical. First, convection near the cusp heads duskwards and dawnwards for *By*− and *By*+, respectively. This can be attributed to tension due to the *By* effect. From the right panel in Fig.3, it can be seen that corresponding to the condition in which convection at the cusp is duskward; the morning sector region 1 current stretches along the higher-latitude side of the evening sector region 1 current and extends to the evening sector. The dynamo is thought to lose its symmetry and to acquire a 3D structure. Many problems remain to be resolved, such as the 3D structure of the dynamo and the relationship between the morning sector region 1 current structure extending to the duskside and the cusp FAC.

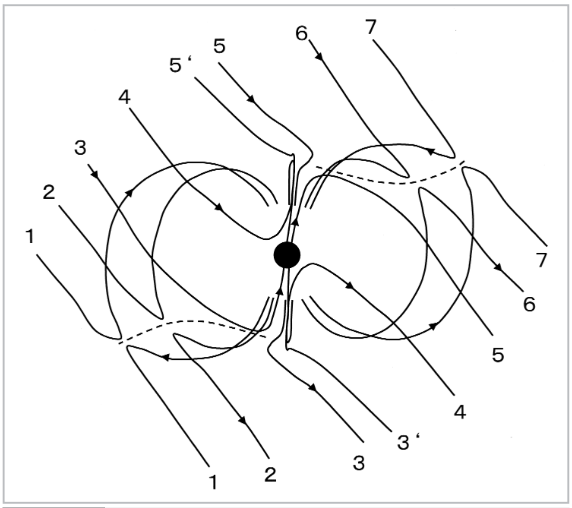

Fig.11 Dayside reconnection for southward IMF

Next, in the central part of the polar cap, convection heads straight in the 12-0 o'clock direction for *By*−, whereas it is oblique for *By*+ in the 9-21 o'clock direction. The positions of the evening and morning sector cells are shifted to the dayside and nightside,

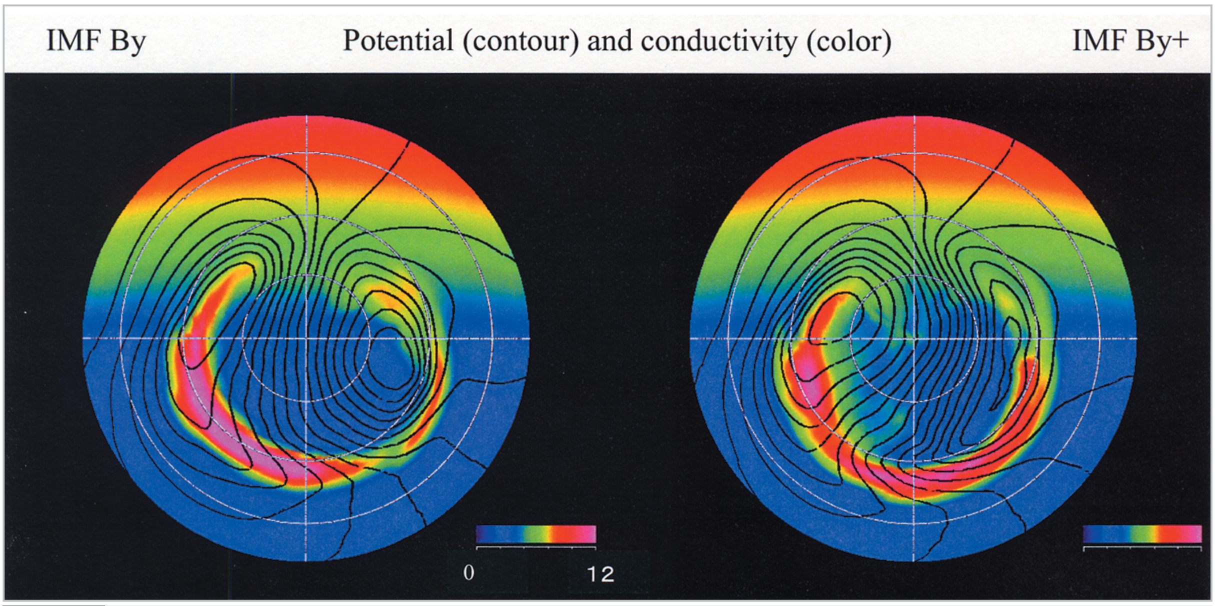

Fig.12 *By effect on ionospheric potential distribution*
Electric conductivity and potential are represented by color scale and contours, respectively. The left and right plots are for negative and positive *By*, respectively.

respectively, for both *By*− and *By*+, displaying a clockwise rotation. On the whole, the evening sector cell is dominant. This results from charge accumulation along the terminator line which prevents discontinuity in the Hall current arising from the difference in conductivity between the day and night sectors, to modulate the potential distribution (*Atkinson and Hutchison*, 1978). However, this is insufficient to generate a clockwise rotation, which is considered to be a manifestation of a more global balance (*Tanaka*, 2001).

In the night sector, convection is strongly affected by the auroral oval. Near midnight, the equipotential lines in the oval are deflected dawnward. This corresponds to the generation of Cowling conductivity in response to the westward electrojet (WEJ). Near midnight, the electrojet is always westward, and so the equipotential lines cannot be deflected in the opposite direction (duskwards). Therefore, the convection does not display mirror symmetry for *By*. For *By*+, the equipotential lines concentrate in the morning sector at the cusp, and unless these lines are returned to the evening sector in the polar cap, dawnward deflection of the equipotential lines in the auroral oval and the WEJ cannot be produced. This results in oblique equipotential lines within the polar cap. These structures are involved in the generation of the Harang discontinuity (*Harang*, 1946). Within the WEJ, Harang discontinuity is generated by shear at the equatorial edge of the auroral oval, and the eastward electrojet (EEJ) is generated by shear at the poleward edge (*Amm et al.*, 2000). It has been generally accepted that the Harang discontinuity is generated by magnetospheric convections (*Erickson et al.*, 1991), but ionospheric convections are equally likely to be the cause.

The *By* component during southward IMF is involved in the generation of transient phenomena in the cusp ionosphere (such as magnetopause FTE and the related auroral patch, the dayside auroral transient) (*Newell and Sibeck*, 1993). However, some schools of thought prefer a straightforward interpretation of these phenomena in terms of pulsed reconnection, without giving much consideration to the possibility that the dayside reconnection containing *By* may produce a complex magnetospheric structure (*Lockwood et al.*, 1995). Since the ionospheric convection is incompressible, the fast flow at the cusp presents a concentrated region of equipotential lines.

This can be realized either through the generation of a small vortex or, as in Fig.12, by bending the equipotential lines at the cusp in the east-west direction. With pulsed reconnection phenomena, the former is more likely. However, problems relating to field-aligned irregularities (FAI) and the mechanism of dynamo generation remain unresolved in this case. Fluctuation phenomena in the cusp ionosphere should be viewed differently—i.e., ought not to be seen as a strictly localized problem—when considering the cusp's role as an element of magnetospheric convection (as shown in Fig.8) and when considering reconnection involving *By*.

The effect of *By* is significant in dayside reconnection and ionospheric convection. On the nightside in contrast, oblique IMF (large *By*) does not seem to affect the tail structure greatly.

5.2 Obliquely Northward IMF

A due-northward IMF produces a short magnetotail and 4 cell convection in the ionosphere (*Gombosi et al*., 2000). The dayside reconnection occurs simultaneously in both hemispheres on the higher-latitude side of the cusp between the IMF and the closed magnetic field of the short tail. As a result, a closed magnetic field filled with solar wind plasma appears near noon, and another field (isolated from the geomagnetic field) appears in the tail. The closed magnetic field is assimilated by the magnetospheric low-latitude boundary layers (LLBL; *Song and Russell*, 1992), drifts along the flanks to the tail (convection), and then returns to the reconnection point (*Troshichev*, 1990). Due to this structure, a due-northward IMF generally creates a thick LLBL.

In the case of obliquely northward IMF, the convection structure is more complex, with a magnetospheric convection composed of a lobe cell and a merging cell and an ionospheric convection composed of a round cell and a crescent cell (*Crooker et al*., 1998; *Tanaka*, 1999). Here, the lobe and the merging cells are named after their physical structures. The former convection is confined to the interior of the lobe and does not reach the plasma sheet (Fig.13) and remains as perpetually open field lines (Type 1 open magnetic field line). The latter convection reaches the plasma sheet, and through a reconnection process in the tail, experiences an interval of closed magnetic field lines (Type 2 & Type 3 open magnetic field lines) (Fig.14 & 15). In contrast, the round and the crescent cells of the ionosphere are only classified according to external shape. Physically speaking, the round cell consists of both the lobe cell (Type 1 open magnetic file line) and the merging cell

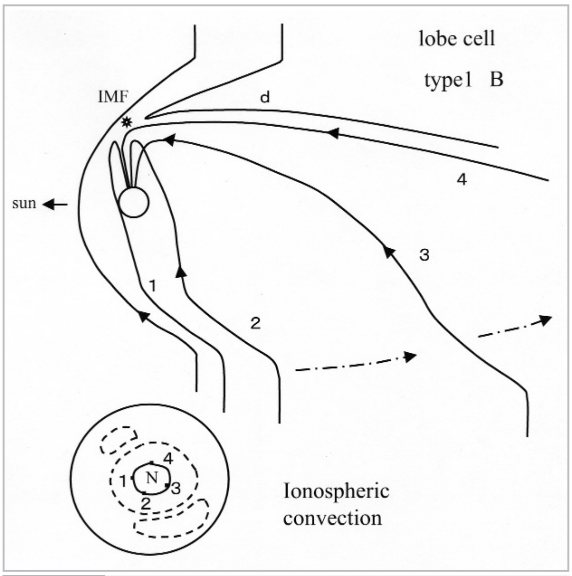

Fig. 13 Lobe cell for obliquely northward IMF (Type 1 magnetic field)

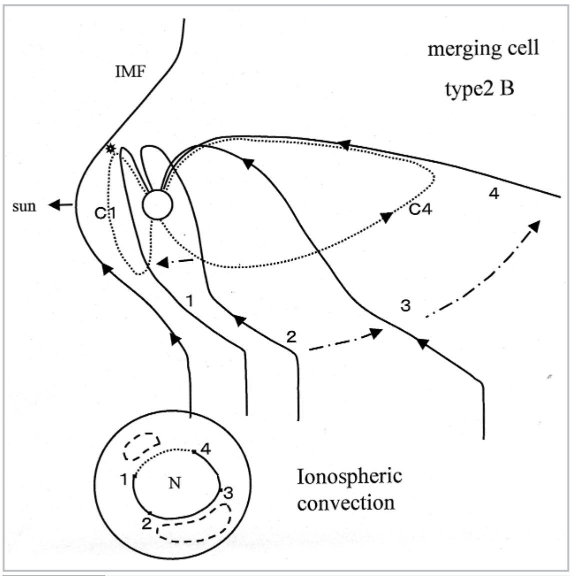

Fig. 14 Merging cell for obliquely northward IMF (Type 2 magnetic field)

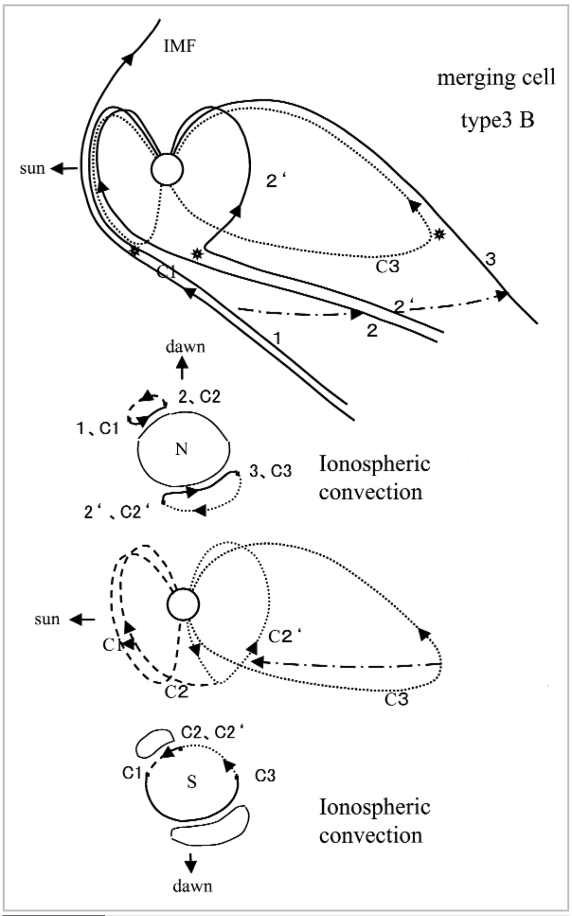

Fig. 15 Merging cell for obliquely northward IMF (Type 3 magnetic field)

(Type 2 open magnetic line), while the crescent cell consists only of the merging cell (Type 3 open field line).

In Fig.13, the lobe cell is initiated by reconnection of the IMF and open magnetic field line 4. This results in the generation of line 1, which is a Type 1 magnetic field line. The reconnection produces an isolated magnetic field line "d" along with line 1. However, line d is positioned away from the Earth and is not a part of the convection. Line 1 remains as an open magnetic field line, convects to positions 2 and 3, and finally returns to the original position at 4. The Type 1 magnetic field line always drifts near the magnetopause and does not reach the plasma sheet. As seen from Fig.13, the source of Type 1 magnetic field lines shifts position in the central part of the round cell inside the ionosphere (*Crooker et al*., 1998).

The merging cell is initiated by the reconnection between the IMF and a closed magnetic field line. Here, the magnetic field lines of the merging cell can be classified as Type 2 on the round cell and Type 3 on the crescent cell in the ionosphere (*Tanaka*, 1999). The apparent differences between these types (viewed in terms of magnetospheric convection) require a somewhat complicated explanation. Type 2, shown in Fig.14, has the same basic convection structure as Type 1 at positions 1, 2, 3, and 4. However, at position 4, the field line becomes a closed magnetic field line (C4) through tail reconnection. It then returns to C1 as a closed magnetic field line. It can be seen from Fig.14 that the source of Type 1 magnetic field lines drifts along the periphery of the round cell in the ionosphere (*Crooker et al*., 1998).

Type 3 magnetic field lines display an even more complex structure, and in addition to the open-closed structure of Type 2 field lines, it features a distinct cell switchover process (Fig.15). When the magnetic field line at 1 created by the dayside reconnection arrives at position 2, it reconnects again with C2' and becomes line 2'. Along with this switchover, the footpoint in the ionosphere also switches from C2 to C2'. Thus, the convection from position 1 to 2 can be considered to relay the open magnetic field line created by reconnection to the crescent cell, producing a third ionospheric cell type (in addition to the round and crescent cell types), which may be referred to as the "exchange" cell (Tanaka, 1999). This structure, present at around 9 o'clock, is a 4-layer structure when seen from the FAC. Whereas *Ohtani and Higuchi* (2000) explained a 4-layer structure based on viscous cells, the exchange cell may be considered an alternative explanation of the 4-layer structure. The Type 3 magnetic field line moves to a position nearest to the plasma sheet, and reconnects with the Type 2 line in the opposite hemisphere inside the plasma sheet. The Type 3 field line displays strange motion inside the magnetosphere. From position 2' to 3 in Fig.15, the Type 3 line progresses from the evening sector to the morning sector, but returns to the evening sector before tail reconnection (*Tanaka*, 1999).

As a result, a magnetotail with a twisted magnetic structure is produced during obliquely northward IMF. The nightside reconnection inside the merging cell takes place under this twisted magnetic field structure. Since two twisted magnetic fields cannot satisfy the antiparallel condition with respect to each other, they undergo an untwisting process at a distance and then reconnect. This is the cause of the strange motion observed with the Type 3 magnetic field line. In this way, the oblique IMF model can explain the formation of the distant-tail neutral line. This is an important initial condition for the substorm growth phase.

The convection flow during a northward IMF, as explained above, is slower than that for a southward IMF. This is because, generally, IMF connecting to the geomagnetic field through reconnection structures is decreased, and results in an extremely suppressed penetration of electric field from the solar wind. From Figs.13, 14, and 15, it can be observed that IMF with larger y-coordinate values convects antisunward in the ionosphere deeper in the morning sector, and produces an electric field in the dawn-to-dusk direction in the ionosphere. However, this interpretation is based on the **EJ** paradigm, and does not apply to Fig.10. It is necessary to explain this convec-

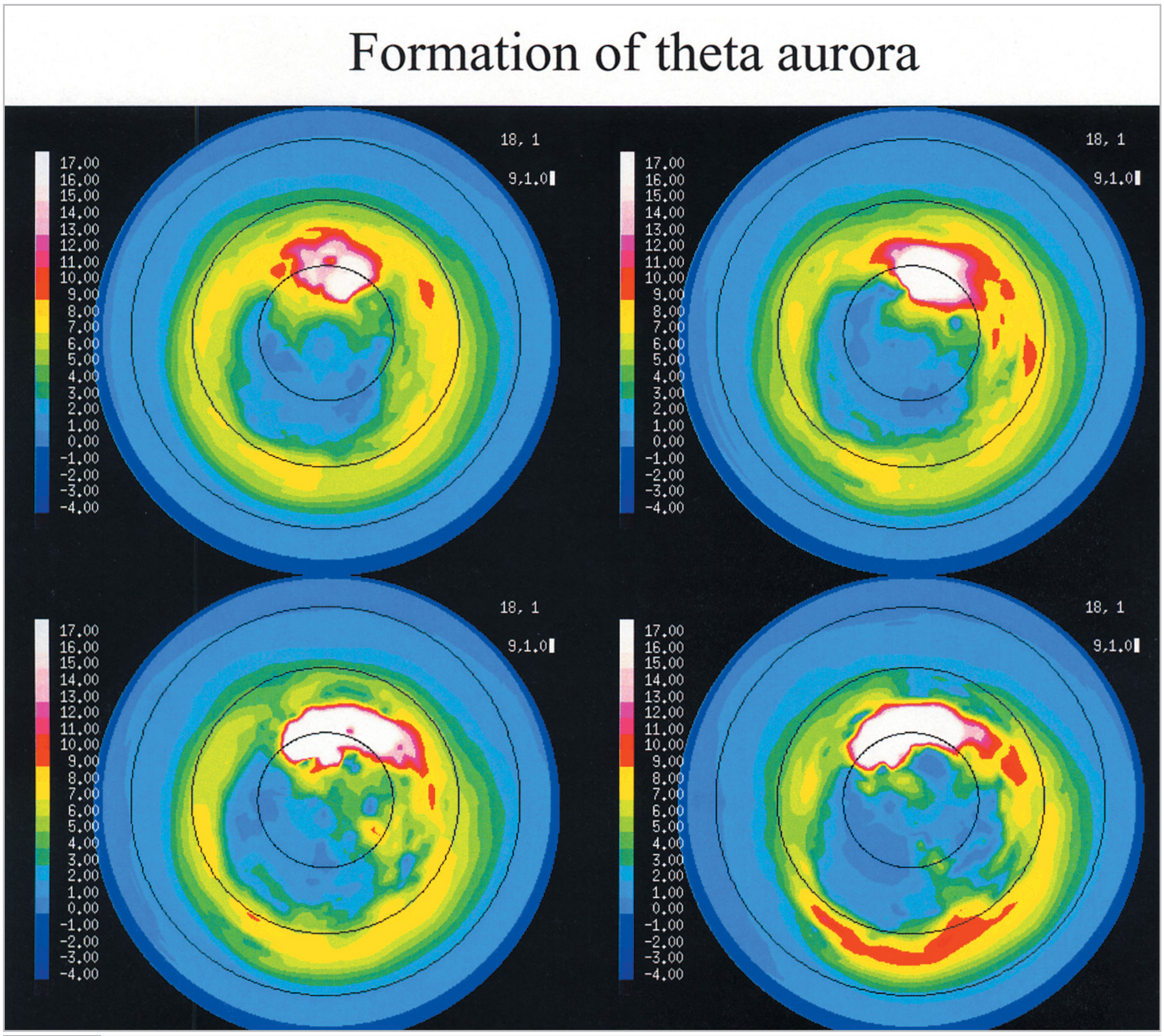

Fig.16 *Formation of a theta aurora*

The plots proceed in the following chronological order (0 to 25 min): upper-right, upper-left, lower-right, and lower-left.

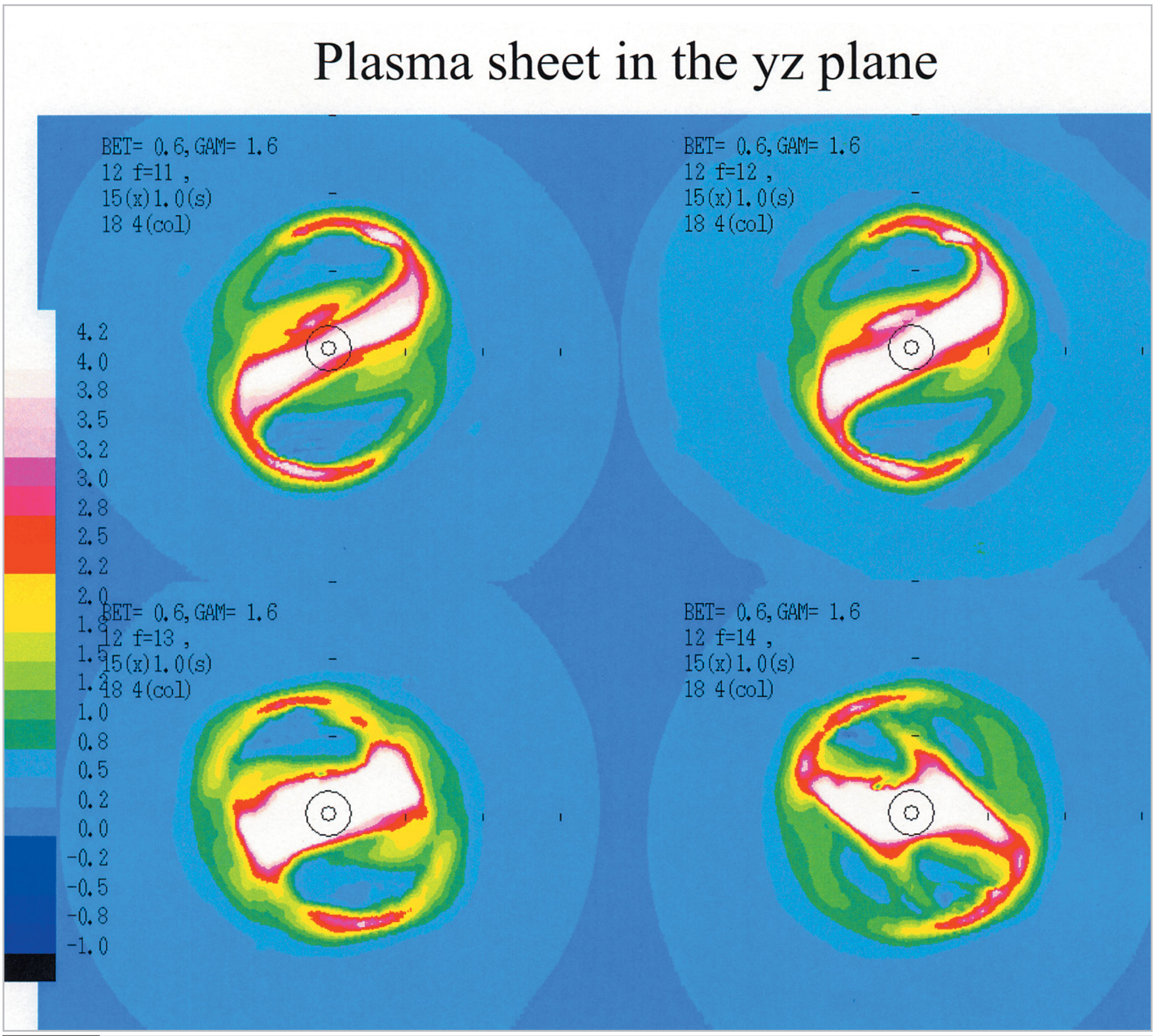

Fig.17 *Changes in the plasma sheet structure during theta aurora formation*
The plots are for the same time points as in Fig. 16.

tion in terms of the dynamo and FAC, even for a northward IMF. A week convection under northward IMF should be interpreted as a result of insufficient release of tension, as seen in Fig.8, which leads to less increased internal energy in the cusps.

5.3 The Effects of IMF By and Theta Aurora

One of the most interesting phenomena of the magnetosphere during northward IMF is the theta aurora. To study the theta aurora, it is necessary to have a firm understanding of the magnetospheric structure during northward IMF. A theta aurora appears after a large shift in the *By* component involving a sign change, during relatively long durations of northward IMF having absolute value exceeding 10 nT (*Cumnock et al.*, 1997). Fig.16, 17, and 18 show the results of simulation under the above conditions, with a negative-to-positive shift in *By*. Fig.16 shows the development of a pressure distribution in the ionosphere projected from the magnetosphere. In the beginning, an auroral oval expands in the morning sector, and eventually, a gap appears between the primary oval and this extended auroral oval. The detached part of the auroral oval drifts further duskwards and becomes a theta aurora. The behavior of the auroral oval during this process agrees well with actual observations (*Cumnock et al.*, 1997).

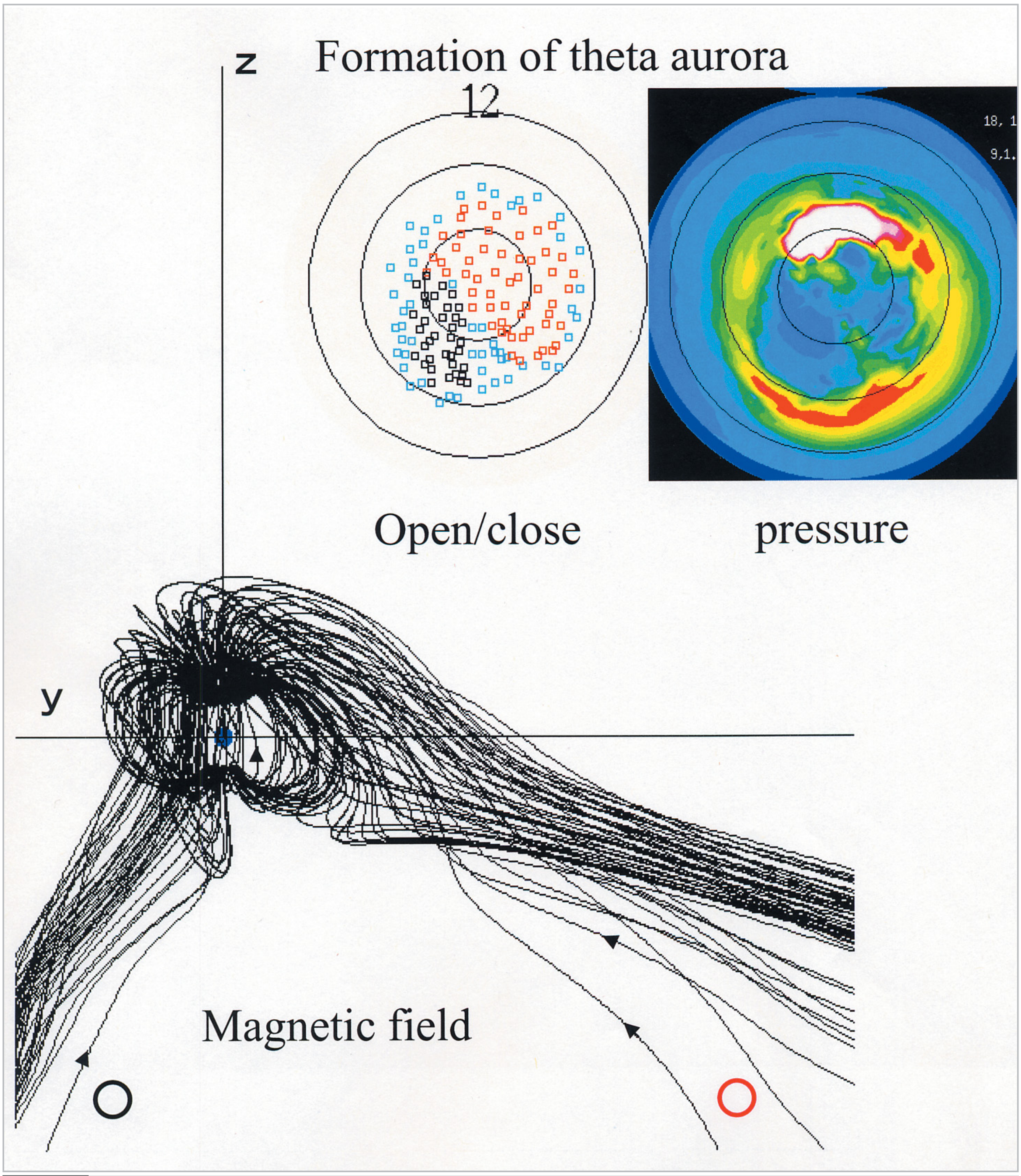

Fig.18 *Magnetic field topology during theta aurora formation*

Black, red, and blue dots in the ionosphere show the sources of *By*-, *By*+, and closed magnetic fields, respectively. Circles represent 60˚, 70˚, and 80˚ latitudes. The lower-right-hand plot in Fig.16 is shown for comparison.

How does the magnetospheric structure respond to these changes in the ionosphere? Fig.17 shows the temperature distribution of a developing plasma sheet at various stages on the y-z plane at x = 15Re. This figure corresponds to the sight line from the tail to the Earth. In the beginning, the plasma sheet is twisted in the counterclockwise direction, corresponding to negative *By*. Some time after *By* turns positive, the twisted structure weakens and the plasma sheet thickens. As time progresses, the plasma sheet begins to twist in the opposite direction, and a kink appears between the central part and the edge. This kink, projected onto the ionosphere, is the theta aurora. At this stage, the northern lobe separates into the morning and evening parts. In the northern hemisphere, the former consists of a lobe derived from a new IMF with positive *By*, and the latter consists of a lobe derived from the old IMF with negative *By*. It can be clearly seen from Fig.18 that there are counterparts to this structure in the ionosphere. Fig.18 presents the magnetic field structure observed from the tail, showing with this footpoint in the ionosphere. In the morning sector, there is a new polar cap with a magnetic field connected to positive *By*, and in the evening sector, there is an old polar cap with a magnetic field connected to negative *By*. Note here that the closed magnetic field lines are accumulated above the theta aurora, extending to the polar cap.

The various morphologies obtained in simulations can be explain from the convection structure during northward IMF. Let us examine the convection in the northern hemisphere, assuming that the *By* has shifted from negative to positive. In the beginning, there is a crescent cell in the evening sector and a round cell in the sector from the center of the polar cap to the morning (*Tanaka*, 1999). The Type 2 magnetic field lines of the merging cell, which have opened at the cusp, drift in the counterclockwise direction over the round cell. Upon reaching nightside, the Type 2 magnetic field lines reconnect with the Type 3 magnetic field lines that have drifted over the crescent cell in the morning sector in the southern hemisphere (same as the structure shown in Fig.15, but reversed in the N-S hemisphere). The resulting closed magnetic field line returns to the reconnection region near the cusp, passing through the magnetosphere in the morning sector. However, when the *By* switches to positive, a new round cell drifting in a clockwise direction appears at the central part of the polar cap. Thus, the circuit to return to the morning sector is blocked for the closed magnetic field lines created in the old convection. In the new convection, the crescent cell is formed in the morning sector and drifts in the counterclockwise direction, and this also blocks the return path of the closed magnetic field lines created in the old convection. Therefore, the closed magnetic field lines created from the lobe magnetic field with negative *By* accumulate in the nightside, forming a theta aurora.

6 Behavior of a Transient Convection

The study of the structure of the magnetosphere-ionosphere convection system forms the basis of all studies of magnetosphere-ionosphere phenomena. All disturbance phenomena are derived from this fundamental structure, and one can achieve a significant understanding of these phenomena by regarding them as manifestations of variations in convection. Here, we will examine how the convection structure consists of the incompressible ionosphere and compressible magnetosphere and how the magnetosphere responds most efficiently to changes in solar wind conditions while simultaneously maintaining self-consistency.

6.1 Reconstruction of the Ionospheric Convection

Convection is often explained as being induced by the tailward motion of the magnetospheric plasma by the tension from IMF anchored to the solar wind, and by transporting plasma sunwards by the shortening of magnetic field lines after nightside reconnection events. This is because, for a long time, these ingenious ideas on the magnetosphere presented by *Dungey* led many to accept them unconditionally. The well-known problem with this interpretation, leading to inconsistencies, is the problem of different response times of the magnetospheric and ionospheric convections (*Ridley et al.*, 1997; *Khan and Cowley*, 1999; *Murr and Hughes*, 2001).

When the IMF switches northward to southward, ionospheric convection becomes stronger near the cusp, which is consistent with the conventional view that the cusp exists below the dayside reconnection. According to Dungey's image of convection, it takes approximately 30 minutes for fast magnetospheric convection to reach the tail, and thus many believe that the intensity of the nightside ionospheric convection begins to increase after 30 minutes. This perception is based on the erroneous premise that the downstream (nightside) ionospheric convection cannot be induced by the magnetotail unless the change on the dayside has been relayed to the magnetotail. However, in reality, nightside convection responds immediately to changes in IMF, as does dayside convection (*Ridley et al*, 1997; *Murr and Hughes*, 2001). This has been interpreted as the propagation of cusp information to the nightside through the ionosphere at a large Alven velocity (See Chapter 3 for details).

This explanation is equivalent to stating that the ionosphere is incompressible. In other words, it proves that the ionospheric electric field can be expressed by potential, that the motion in the ionosphere is restricted to an eddy (vortex) motion (div$\mathbf{V}$ = 0), and that the magnetic field is stationary ($\partial\mathbf{B}/\partial t = 0$). For ionospheric closure of FAC, Eq. (2) represents necessary and sufficient conditions. Therefore, convection can be generated in the nightside ionosphere if there is a supply of $J_\parallel$. Here, also, the problem lies in the discussion of the actual position and structure of the dynamo. The FAC remains an FAC only in the low-beta region. In the high-beta region, it becomes immediately nonparallel to the magnetic field. This causes the dynamo of the region 1 current to be situated relatively near the dayside (Fig.6). This results in a quick ionospheric response.

This naturally raises the question of whether ionospheric convection can control magnetospheric convection. Such domination of the ionosphere may lead to contradicting states in magnetospheric convection. However, this problem is easily solved, since not only shear motion but also compressible motion are possible in the magnetosphere to accommodate any contradicting states. A typical example of this problem may be found in convection in the substorm growth phase, as explained below.

6.2 Distant-Tail Neutral Line and the Growth Phase

A northward-to-southward turning of the IMF enhances dayside reconnection due to its antiparallel-merging characteristic. Observations have revealed that the progress of magnetospheric convection accompanies a thinning of the plasma sheet, and that in the ionosphere, two-cell convection is induced accompanied by a gradual increase in current intensity. These represent well-known features of the growth phase (*Baker et al.*, 1996). As explained in the previous section, it is predicted that at least 30 minutes is required for the magnetospheric convection to reach the nightside depending on the solar wind velocity. However, it takes the ionosphere only approximately 5 minutes to turn into a two-cell convection involving the nightside. This is clearly the result of selective generation of shear motion by the incompressible ionosphere.

The flaring angle theory is often proposed to explain plasma sheet thinning (*Baker et al*., 1996). Under this theory, the open magnetic field lines accumulate on the nightside due to the transport after reconnection on the dayside, producing a larger flaring angle. Therefore, the lobes are more strongly sailed by solar wind pressure, which leads to increased lobe magnetic pressure. This increased lobe pressure compresses the plasma sheet and thins it. It is obvious that this theory relies upon an extension of the magnetospheric image based on localized MHD balance or single-particle description.

In contrast, from a global magnetospheric image based on convection, plasma sheet thinning is generated due to the "gap" between the magnetospheric and ionospheric convections during the growth of convection (*Tanaka*, 2000b). Fig.19 presents the magnetic topology during the growth phase, 30 minutes after the turning of the IMF orientation from obliquely northward to obliquely southward.

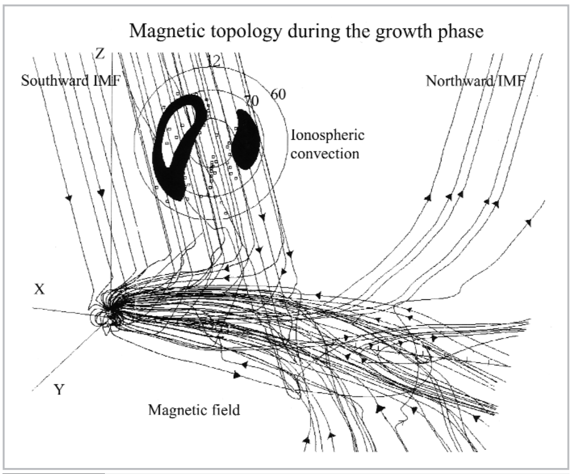

Fig.19 Magnetic field topology during the growth phase 30 minutes after change in IMF

It is evident that the topology still retains features of northward IMF. The southward IMF is present only near the surface of the magnetosphere, and the core part still retains the northward IMF. The mechanism of the growth phase under such a structure is shown in Fig.20. With the development of the dayside reconnection, the magnetospheric convection from the dayside toward the nightside is strengthened. However, the distant-tail neutral line does not immediately disappear, and so the plasma sheet backflow does not immediately increase along with the convection.

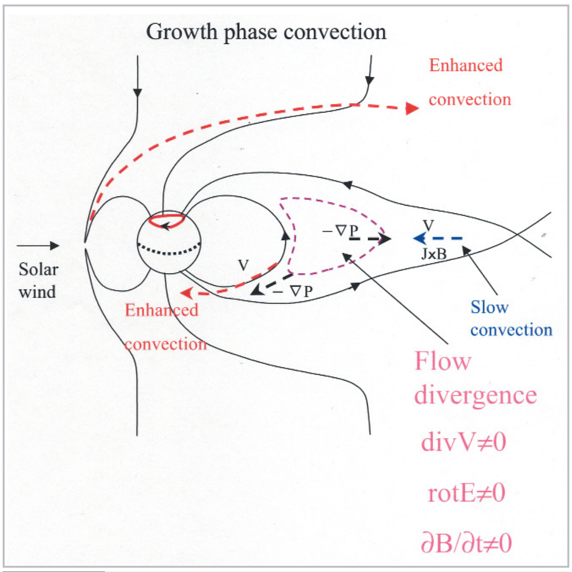

Fig.20 Schematic diagram of growth phase convection

The red lines show the regions of enhanced convection.

This fast forward and slow backward convection accompanies a compressional component and cannot be directly projected onto the ionosphere. However, the ionosphere does not need to incorporate the entire state of the magnetosphere. In this case magnetospheric convection need only be seen from the ionosphere as a shear flow. The magnetospheric convection can generate a shear flow against the ionosphere by creating a divergent flow that sweeps out the plasma accumulated in the plasma sheet to dayside. This causes the outgoing dayward flux from the plasma sheet to exceed the supply flux to the plasma sheet from the distant-tail, resulting in plasma sheet thinning. In this way, the thinning of the plasma sheet during the growth phase is a natural consequence of convection development. In the diagrams presented in Fig.2, the divergent flow corresponds to the condition $\partial \mathbf{B}/\partial t \neq 0$, and thinning is an expected outcome.

6.3 Substorm Onset

No matter how large in magnitude the magnetosphere-ionosphere disturbance may be, it would not be regarded as a substorm if it were to start gradually. A major object of substorm study is to find an explanation for the appearance of discontinuity at onset. A dipolarization event that definitely corresponds to the condition $\partial \mathbf{B}/\partial t \neq 0$ characterizes onset, and reveals the convergent property of magnetospheric convection (Fig.2). Naturally, this convergent motion is not projected onto the ionosphere. Conversely, the magnetosphere needs to generate such motion as that confined to the magnetosphere.

The near-earth neutral line (NENL) model in the lower panel of Fig.21 (*Baker et al.*, 1996) explains flow convergence (dipolarization) as a pileup of fast flow from the NENL. Therefore, the motion is in a fast wave mode, in which both the magnetic field and fluid are similarly compressed. This produces tailward pressures that are balanced by the earthward dynamic pressure. This structure is the same as that for the bow shock in Fig.6, and the negative $\mathbf{J}\cdot\mathbf{E}$ generates a dawnward current.

This current is considered to correspond to the current wedge. The substorm discontinuity in this model results from the rapid development of NENL. The reconnection must be an instability in this case, and is regarded as a result of kinetic processes. However, this model is inconsistent with the results shown in Fig.9. In this model, the onset proceeds from the tail to the inner magnetosphere (steps 1, 2, and 3 in Fig.21, bottom). The other weakness of this model lies in the discordance in the brightening order of quiet arcs (which proceed from the equator to polar direction) that are already present before the onset. Furthermore, it fails to explain the fact that substorm onset is triggered by a northward turning of IMF (*Lyons*, 1997).

Performing a rotation operation on depolarization corresponds to the development of a current disruption (CD), and under the **BV** paradigm, these two are equivalent processes.

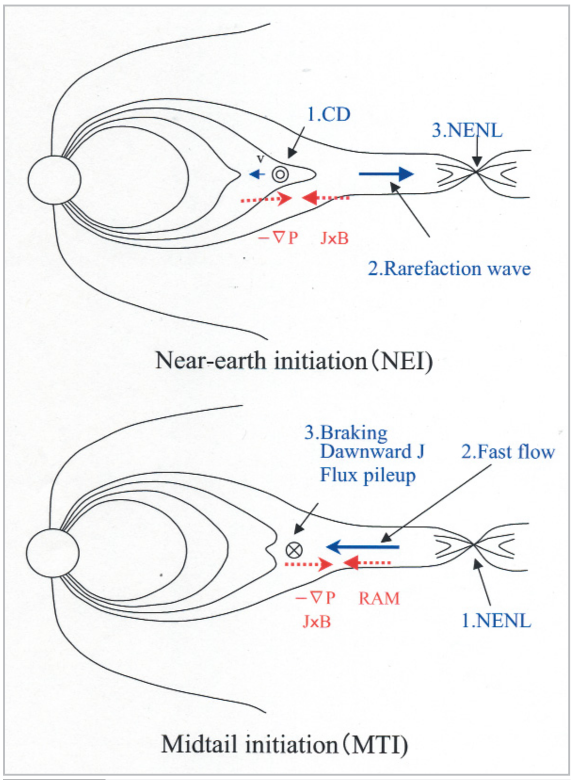

Fig.21 Schematic diagrams of two substorm models

Top and bottom figures represent CD and NENL models, respectively. Both models assume a principal cause for the onset, and hence the resulting effects occur in sequence.

In contrast to the NENL model, the CD model attributes the substorm discontinuity to the CD (depolarization). In the CD model, disturbance produced as a result of CD propagates to the tail and triggers the NENL (Fig.21, top; *Lui*, 1996). In this model, the onset proceeds from the inner magnetosphere to the tail (steps 1, 2, and 3 in Fig.21, top). The CD is a kinetic process and is also unstable. Supporters of this model associate the severe magnetic oscillations accompanying depolarization with non-MHD processes, and seem to believe that there may even be a separation between the magnetic field and plasma. Therefore, this model is interpreted under the **EJ** paradigm. The CD model is consistent with the brightening order of the quiet arcs.

The two models above both attribute the cause of onset to local instabilities. In contrast, the state transition model (*Tanaka*, 2000b) regards the onset as extension of the development process of convection. During the growth phase, the balance between plasma pressure and magnetic pressure in the z-direction is the dominating element in the force balance, and depolarization is considered to be a restoration of tension resulting from the shrinkage of the elongated magnetic field. The restored tension balances with the tailward $-\nabla P$ from the high-pressure region created by injection. In other words, tension confines the plasma and enables convergence of the convection, allowing convection motion to be driven even when the magnetosphere and ionosphere are partially out of sync. This driven convection motion corresponds to the onset. Plasma accumulates along the magnetic field lines without compression of the magnetic field, and forms slow wave variations. Fig.22 shows the development of pressure distribution within the plasma sheet. The variations in pressure distribution are similar to those observed by *Kistler et al.* (1992), and generate a maximum within 10 Re after onset. These variations are rapid, and within 1 minute, a transition in distribution occurs from the growth phase to the expansion phase.

The state-transition model can also explain

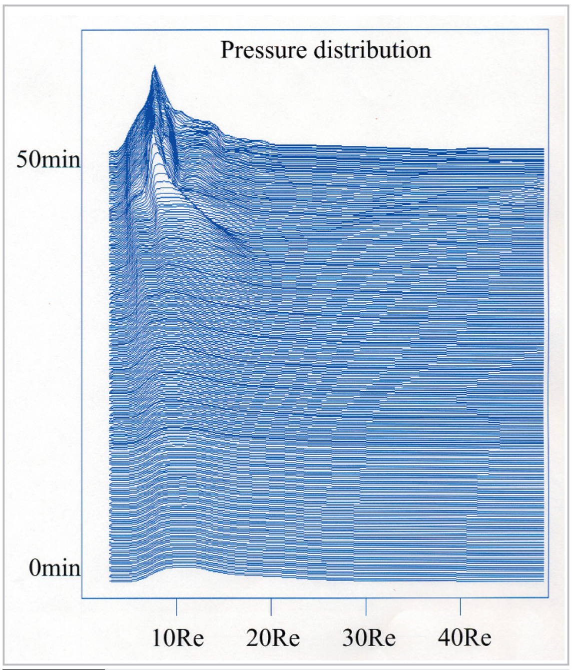

Fig.22 Development of plasma sheet pressure distribution during substorms

the triggering effect caused by the northward-turning of IMF. The deceleration of the ionospheric convection reduces the flux exiting the plasma sheet to the dayside, creating a region prone to flow convergence. The triggering effect by northward-turning of IMF is also explained by *Lyons* (1995). However, *Lyons'* theory attempts to explain the triggering effect as originating from the deceleration of convection caused by the penetration of the weakened solar wind electric field into the magnetosphere; this leads to the mistake of the **EJ** paradigm pointed out by *Parker* (2000).

The NENL model and the CD model both assume that there must be a central player initiating the onset. In contrast, there is no central player in the state transition model. The state transition model resembles the economic model of major depressions, the Ising model for magnetization, or the avalanche model for substorms (*Chapman et al.*, 1998). These models are all based on cooperative phenomena, and no central players exist. Instead, in these models, many similar elements coexist and interact with one another. The state transition of the interacting systems corresponds to the conditions of a major depression and of magnetization. The onset of a substorm is the occurrence of state transition in the interacting system, as shown in Fig.10. A substorm does not involve as many elements as the economic model or the model for magnetic bodies. However, all elements in substorm have characteristic topologies. Since the conditions differ significantly from those of a typical complex system (found in economic models and models for magnetic bodies), we will refer to the substorm as a composite system. The concept of this type of state transition has also been suggested by *Atkinson* (1991), followed by *Tanaka* (2000b).

6.4 Pseudo Breakup and SMC

Pseudo breakup and steady magnetospheric convention (SMC, or convection bay) are phenomena resembling a substorm but which are grouped in a different category. The pseudo breakup displays a common morphology with substorms until the onset. However, it does not accompany poleward expansion or a westward traveling surge (WTS), and terminates before changes are propagated to the whole magnetosphere (*Pulkkinen et al.*, 1998). The magnitude of disturbance in an SMC is comparable to that of the substorm, but an SMC progresses to the expansion phase without displaying a clear discontinuity, or onset (*Yahnin et al.*, 1994; *Sergeev et al.*, 1996). In an SMC, a strong, stationary two-cell ionospheric convection is realized.

A pseudo breakup can be explained in terms of the NENL model as a mid-course termination of an initiated reconnection. In contrast, in the state transition model, it can be interpreted as follows. Normally, state transition is initiated in the inner magnetosphere with the extinction of the distant-tail neutral line shown in Fig.19, and the substorm proceeds to the expansion phase. However, if state transition occurs before the extinction of the distant-tail neutral line shown in Fig.19, the discontinuity at onset is realized, but the NENL cannot be formed at this stage due to the presence of the core structure shown in Fig.19. This results in a failure to proceed to the expansion phase, and instead, the event ends in a pseudo breakup. If convection is promoted without state transition or after the state transition has been initiated, and the state of no distant-tail neutral line is maintained , then the event is an SMC. In this way, the state transition model provides simple explanations for pseudo breakups and SMC.

6.5 SC and Convection

Sudden commencement (SC) is a nonstationary response of the magnetosphere when subject to sudden and strong increase in dynamic pressure of the solar wind. The magnetosphere must achieve a new state of equilibrium to incorporate this strong dynamic pressure. This is a classic problem, and has been the subject of extended study; in first-order approximation, this response is interpreted as an increase in Chapman-Ferraro current. This has often led to the misapplication of Bio-Savart's Law in an attempt to solve the problem. As we have repeatedly stressed in previous sections, variations in the magnetosphere-ionosphere system must be regarded as a response in convection. The magnetosphere is not a vacuum, and therefore, SC must be interpreted not in terms of Bio-Savart's Law, but in terms of convection physics or in terms of composite system. The pattern of geomagnetic field variation during a typical SC involves the initial short-period reduction of horizontal components, followed by a rapid increase in horizontal components, after which this increased level is maintained for some time. The initial reduction is referred to as the preliminary reverse impulse (PRI) and the following increase is called the main impulse (MI).

Results of recent SC studies using MHD simulations have revealed the nature of the SC in terms of composite system. Figs.23 and 24 show the simulation results of SC developing out of the conditions shown in Figs.13, 14, and 15. Fig.23 shows the dayside magnetosphere structure, the magnetic field, and current lines at the PRI stage. At this stage, a compressional motion is propagated within the magnetosphere, and a polarization current is formed at the propagation front. The non-uniformity of the medium couples the polarization current with the FAC. The middle panel shows how a PRI current loop is formed from the increased CF current, polarization current, and FAC. From the top panel, it can be seen that the magnetic field extending from the region of FAC inflow is located far within the

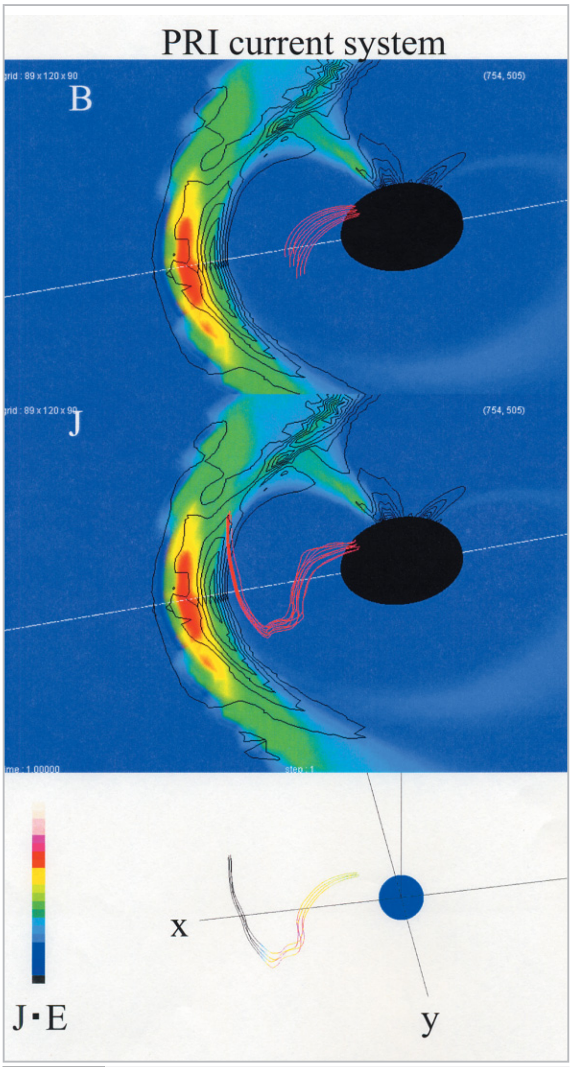

Fig.23 *Dayside magnetic field topology, electric current system, and energy conversion (J•E) during preliminary reverse impulse (PRI)*

The color scale represents the pressure distribution on the 12-0 meridian and equatorial planes, and the red line represents the magnetic field extending from the region where PRI is most observed. The contours represent the intensity of electric current. The middle panel is the same as the top panel, except for the red line representing electric current. In the bottom panel, **J·E** is superimposed on the electric current.

magnetopause. From **J•E** in Fig.23, it can be seen that the CF current is the dynamo, and that work is done by the solar wind dynamic pressure. Since momentum is transferred ahead at the polarization current, the compressed magnetospheric magnetic field pushes the magnetospheric plasma, and **J•E** is positive. Even though the topology is different, the structure shown in Fig.10 is generally established for the PRI.

Fig.24 illustrates MI convection. The panel on the lower right shows the development of an ionospheric convection after arrival of high dynamic pressure. The second plot still shows residual of PRI. MI develops in the third panel, and then becomes gradually damped in the ensuing panels. The upper-left and central panels show the ionospheric convection and magnetic field structure at the timing between plots 3 and 4 in the lower-right panel. The small circles in the ionospheric convection represent the footpoints of the magnetic field lines presented in the central panel. At high latitudes, a lobe cell is seen accompanied by northward IMF. In contrast, the ionospheric convection cells at low latitudes in the dusk sector accompany region 1 currents; this is MI convection. The two groups of small circles in the ionospheric convection show the flow paths of footpoint of magnetic field lines constructing the lobe cell and the MI cell. The lobe cell structure in the center panel corresponds to that in Fig.13, and consists only of open magnetic field lines. On the other hand, the MI convection has only closed magnetic field lines, and clearly differs from convections induced by reconnection. At the end of PRI, the dayside magnetic field is excessively compressed compared to the nightside, and is in a state of pressure imbalance. The MI convection is generated to restore balance, using this dayside over-compression as an energy source. As expected, convection is a process that transfers the magnetosphere into a new state of equilibrium, as shown in Fig.10.

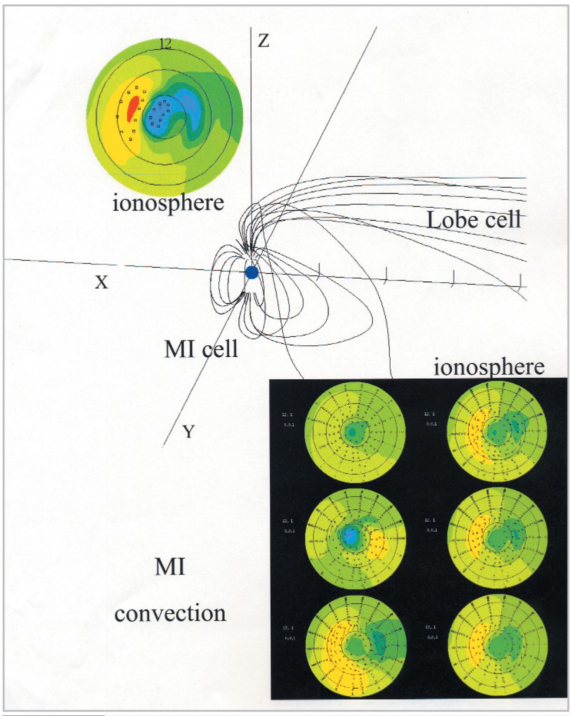

Fig.24 *Convection of the main pulse (MI)*

The upper-left figure shows the ionospheric potential and the footpoints of the magnetic field, the panel in the center shows the magnetic field topology, and the lower-right panel represents the development of the ionospheric potential.

The magnetic variations during SC are strong in the initial stage, or PRI, when energy is supplied to the magnetosphere. During MI, when this energy is consumed, the magnetospheric variations are relatively mild. Nevertheless, PRI produces only slight variations in the ionosphere, while the MI is observed as a large disturbance. This is a direct consequence of the fundamental dynamics of the magnetosphere-ionosphere system shown in Fig.2. In other words, PRI is a compression motion and is basically invisible in the ionosphere. Due to the non-uniformity of the medium, there occurs only a small disturbance as PRI due to mode conversion in the magnetosphere. In contrast, the MI is a shear motion coupled between the magnetosphere and ionosphere, and can therefore be observed as a large disturbance.

7 Conclusions

Convection is the fundamental process of magnetosphere physics. The main problem in understanding this process lies in determining how the magnetosphere and the ionosphere maintain self-consistency while responding to given solar wind conditions. The physics underlying any space weather phenomena can be identified by examining how the convection structure shown in Fig.10 can be realized in a self-consistent manner, whether the phenomena consist of substorms, SMC (steady magnetospheric convection), pseudo breakup, SC (sudden commencement), or geomagnetic storms.

The physics of magnetosphere-ionosphere coupling has been described in terms of the physics of complex systems, taking into consideration the importance of self-consistency in the magnetosphere-ionosphere coupling, the importance in the earth and planetary sciences of treating systems with topology, and the possiblity of state transitions as cooperative phenomena within entire systems.

References

1 Akasofu, S. -I., "The development of the auroral substorm", Planet. Space Sci., 12, 273, 1964.

2 Amm, O., P. Janhunen, H. J. Opgennoorth, T. I. Pulkkinen, and A. Viljanen, "Ionospheric shear flow situation observed by the MIRACLE network, and the concept od Harang discontinuity, in Magnetospheric current systems ", Geophys. Monogr. Ser., edited by S. Ohtani et al., p.227, AGU, Washington, D. C., 2000.

3 Atkinson, G., "A magnetosphere WAGS the tail model of substorms, in Magnetospheric substorms", Geophys. Monogr. Ser., Vol. 64, edited by J. R. Kan, T. A. Potemra, S. Kokubun, and T. Iijima, p. 191, AGU, Washington D.C., 1991.

4 Atkinson, G., and D. Hutchison, "Effect of the day night ionospheric conductivity gradient on polar cap convection flow ", J. Geophys. Res., 83, 725, 1978.

5 Axford, W. I., and C. O. Hines, "A unifying theory of high latitude phenomena and the geomagnetic storm ", Can. J. Phys., 39, 1433, 1961.

6 Baker, D. N., T. I. Pulkkinen, V. Angelopoulos, W. Baumjohann, and R. L. McPherron, "Neutral line model of substorms: Past results and present view ", J. Geophys. Res., 101, 12,975, 1996.

7 Chapman, S. C., N. W. Watkins, R. O. Dendy, P. Helander, and G. Rowlands, "A simple avalanshe model as an analogue for magnetospheric activity", Geophys. Res. Lett., 25, 2397, 1998.

8 Cowley, S. W. H., "A qualitative study of the reconnection between the Earth's magnetic field and an interplanetary field of arbitrary orientation ", Radio Sci., 8, 903, 1973.

9 Cowley, S. W. H., "Magnetosphere-ionosphere interactions: A tutorial review, in Magnetospheric current systems ", Geophys. Monogr. Ser., edited by S. Ohtani et al., p.91, AGU, Washington, D. C., 2000.

10 Crooker, N. U., "Morphology of magnetic merging at the magnetopause ", J. Atmos. Terr. Phys., 52, 1123, 1990.

11 Crooker, N. U., J. G. Lyon, and J. A. Fedder, "MHD model merging with IMF By: Lobe cells, sunward polar cap convection, and overdraped lobes ", J. Geophys. Res., 103, 9143, 1998.

12 Cumnock, J. A., J. R. Sharber, R. A. Heelis, M. R. Hairston, and J. D. Craven, "Evolution of the global aurora during positive IMF Bz and varying IMF By conditions ", J. Geophys. Res., 102, 17,489, 1997.

13 Dungey, J. W., "Interplanetary magnetic field and the auroral zones ", Phys. Rev. Lett., 6, 47, 1961.

14 Erickson, G. M., R. W. Spiro, and R. A. Wolf, "The physics of the Harang discontinuity ", J. Geophys. Res., 96, 1633, 1991.

15 Gombosi, T. I., K. G. Powell, and B. van Leer, "Comment on Modeling the magnetosphere for northward interplanetary magnetic field: Effects of electrical resistivity by Joachim Raeder ", J. Geophys. Res., 105, 13,141, 2000.

16 Harang, L., "Polar geomagnetic storms", J. Geophys. Res., 51, 353,1946.

17 Harel, M., R. A. Wolf, P. H. Reiff, R. W. Spiro, W. J. Burke, F. J. Rich, and M. Smiddy, "Quantitative simulation of a magnetospheric substorm, 1, Model logic and overview ", J. Geophys. Res., 86, 2217, 1981.

18 Heppner, J. P., and N. C. Maynard, "Empirical high-latitude electric field models ", J. Geophys. Res., 92, 4467, 1987.

19 Iijima, T., "Field-aligned currents in geospace: Substance and significance, in Magnetospheric current systems ", Geophys. Monogr. Ser., edited by S. Ohtani et al., p.107, AGU, Washington, D. C., 2000.

20 Iijima, T., and T. A. Potemra, "The amplitude distribution of field-aligned currents at northern high latitudes observed by Triad ", J. Geophys. Res., 81, 2165, 1976.

21 Kamide, Y., W. Sun, and S. -I. Akasofu, "The average ionospheric electrodynamics for the different substorm phases ", J. Geophys. Res., 101, 99, 1996.

22 Khan, H., and S. W. H. Cowley, "Observations of the response time of the high-latitude ionospheric convection to variations in the interplanetary magnetic field using EISCAT and IMP-8 data ", Annales Geophysicae, 17, 1306, 1999.

23 Kistler, L. M., E. Mobius, W. Baumjohann, and G. Paschmann, "Pressure changes in the plasma sheet during substorm injection ", J. Geophys. Res., 97, 2973, 1992.

24 Lockwood, M., S. W. H. Cowley, P. E. Sandholt, and U. P. Lovhaug, "Causes of plasma flow bursts and dayside auroral transients: An evaluation of two models invoking reconnection pulses and changes in the Y component of the magnetosheath field ", J. Geophys. Res., 100, 7613, 1995.

25 Lui, A. T. Y., "Current disruption in the earth's magnetosphere: Observations and models ", J. Geophys. Res., 101, 13,067, 1996.

26 Lui, A. T. Y., "Electric current approach to magnetospheric physics and the distinction between current disruption and magnetic reconnection, in Magnetospheric current systems ", Geophys. Monogr. Ser., edited by S. Ohtani et al., p.31, AGU, Washington, D. C., 2000.

27 Lyons, L. R., "A new theory for magnetospheric substorms", J. Geophys. Res., 100, 19,069, 1995.

28 Lyons, L. R., G. T. Blanchard, J. C. Samson, R. P. Lepping, T. Yamamoto, and T. Moretto, "Coordinated observation demonstrating external substorm triggering ", J. Geophys. Res., 102, 27,039, 1997.

29 Murr, D. L., and W. J. Hughes, "Reconfiguration timescales of ionospheric convection ", Geophys. Res. Lett., 28, 2145, 2001.

30 Newell, P. T., and D. G. Sibeck, "By fluctuation in the magnetosheath and azimuthal flow velocity transients in the dayside ionosphere ", Geophys. Res. Lett., 20, 1719, 1993.

31 Ogino, T., R. J. Walker, M. Ashour-Abdalla, and J. M. Dawson, "An MHD simulation of the effects of interplanetary magnetic field By component on the interaction of the solar wind with the earth's magnetosphere during southward interplanetary magnetic field ", J. Geophys. Res., 91, 10,029, 1986.

32 Ohtani, S., and T. Higuchi, "Four-sheet structure of dayside field-aligned currents: Statistical study", J. Geophys. Res., 105, 25,317, 2000.

33 Parker, E. N., Newton, Maxwell, and Magnetospheric Physics, in Magnetospheric current systems, Geophys. Monogr. Ser., edited by S. Ohtani et al., p.1, AGU, Washington, D. C., 1999.

34 Pulkkinen, T. I., D. N. Baker, M. Wiltberger, C. Goodrich, R. E. Lopez, and J. G. Lyon, "Pseudobreakup and substorm onset: Observations and MHD simulations compared ", J. Geophys. Res., 103, 14,847, 1998.

35 Ridley, A. J., G. Lu, C. R. Clauer, and V. O. Papitashvili, "Ionospheric convection during nonsteady interplanetary magnetic field conditions ", J. Geophys. Res., 102, 14563, 1997.

36 Ruohoniemi, J. M., and R. A. Greenwald, "Statistical patterns of high-latitude convection obtained from Goose Bay HF radar observations ", J. Geophys. Res., 101, 21,743, 1996.

37 Sergeev, V. A., R. J. Pellinen, and T. I. Pulkkinen, "Steady magnetospheric convection: A review of recent results ", Space Sci. Rev., 75, 551, 1996.
38 Siscoe, G. L., N. U. Crooker, G. M. Erickson, B. U. O. Sonnerup, K. D. Siebert, D. R. Weimer, W. W. White, and N. C. Maynard, "Global geometry of magnetospheric currents inferred from MHD simulations, in Magnetospheric current systems ", Geophys. Monogr. Ser., edited by S. Ohtani et al., p.41, AGU, Washington, D. C., 2000.
39 Song, P., and C. T. Russell, "Model of the formation of the low-latitude boundary layer for strongly northward interplanetary magnetic field ", J. Geophys. Res., 97, 1411, 1992.
40 Sonnerup, B. U. O., "Theory of low-latitude boundary layer ", J. Geophys. Res., 85, 2017, 1980.
41 Stern, D. P., "The origin of Birkeland current ", Rev. Geophys., 21, 125, 1983.
42 Tanaka, T., "Generation mechanisms for magnetosphere-ionosphere current systems deduced from a three-dimensional MHD simulation of the solar wind-magnetosphere-ionosphere coupling processes ", J. Geophys. Res., 100, 12,057, 1995.
43 Tanaka, T., "Configuration of the magnetosphere-ionosphere convection system under northward IMF condition with non-zero IMF By ", J. Geophys. Res., 104, 14,683, 1999.
44 Tanaka, T., "Field-aligned current systems in the numerically simulated magnetosphere, in Magnetospheric current systems ", Geophys. Monogr. Ser., edited by S. Ohtani et al., p.53, AGU, Washington, D. C., 2000a.
45 Tanaka, T., "The state transition model of the substorm onset ", J. Geophys. Res., 105, 21,081, 2000b.
46 Tanaka, T., "IMF By and auroral conductance effects on high-latitude ionospheric convection ", J. Geophys. Res., 106, 24,505, 2001.
47 Troshichev, O. A., "Global dynamics of the magnetosphere for northward IMF conditions ", J. Atmos. Terr. Phys., 52, 1135, 1990.
48 Weimer, D. R., "Models of high-latitude electric potentials derived with a least error fit of spherical harmonic coefficients ", J. Geophys. Res., 100, 19,595, 1995.
49 Yahnin, A., M. V. Malkov, V. A. Sergeev, R. J. Pellinen, O. Aulamo, S. Vennerstrom, E. Friis-Christensen, K. Lassen, C. Danielsen, J. D. Craven, C. Deehr, and L. A. Frank, "Features of steady magnetospheric convection ", J. Geophys. Res., 99, 4039, 1994.

***TANAKA Takashi**, Dr. Sci.*

Professar of Graduate School of Science, Kyusyu University

Magnetosphere-Ionosphere Physics