GRADUAL PENETRATION OF IMF B_y-COMPONENT INTO THE CUSP AND ASSOCIATED FIELD-ALIGNED CURRENT

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Abstract: A transitional model is proposed to show how a pair of field-aligned currents is generated by IMF B_y-component in the cusp region. It is based on the idea of magnetic induction which has a relation to the magnetic shielding current. Originally, the current system which shields out IMF B_y-component from the earth's magnetosphere flows along the magnetopause-boundary layer. However, since the solar plasma can go through the high-latitude magnetopause, the current system can enter into the entry layer. When the current system arrives at a high-altitude cusp where the solar plasma flows away toward the plasma mantle, the magnetic disturbance accompanied by the shielding current begins to descend independently of the solar plasma flow. As it descends, the MHD frozen-in condition becomes satisfied and a magnetic disturbance perpendicular to the geomagnetic field propagates along the cusp field lines as an traveling rotational discontinuity. On the trail of the magnetic disturbance, field-aligned currents remain at both low-latitude and high-latitude sides of the cusp as stationary rotational type discontinuities with weak normal component of magnetic field. When the magnetic disturbance reaches the ionosphere, the descent stops and a quasi-steady state is achieved. In this state, the magnetic shielding current on the surface of the traveling discontinuity turns to the ionospheric Pedersen current. Thus, the current circuit of a pair of cusp field-aligned currents and the ionospheric Pedersen current can be formed as a consequence of the entrance of the constant shielding current system on the solar sector boundary.

1. Introduction

In the last several years, existence of field-aligned currents generated by y-component of the interplanetary magnetic field (IMF) has been confirmed by a number of observations (WILHJELM *et al.*, 1978; IIJIMA *et al.*, 1978; MCDIARMID *et al.*, 1978; LEVITIN *et al.*, 1982; KAMEI *et al.*, 1983). According to these observations, when IMF has a strong y-component, a pair of field-aligned sheet currents linked by the ionospheric Pedersen current appears in the cusp region above the ionosphere.

The observed B_y-dependent current is shown in Fig. 1. When IMF B_y-component is positive, in other words, z-component of interplanetary electric field is positive, a sheet current flows into (out of) the ionosphere at the low-latitude side of the northern (southern) polar cusp, and flows out of (into) the ionosphere at the high-latitude side. The location of the low-latitude side coincides with the extension of the region 1 field-aligned current to the midnoon sector. The poleward (equatorward) ionospheric Pedersen current links up with these two field-aligned sheet currents, and the dusk-

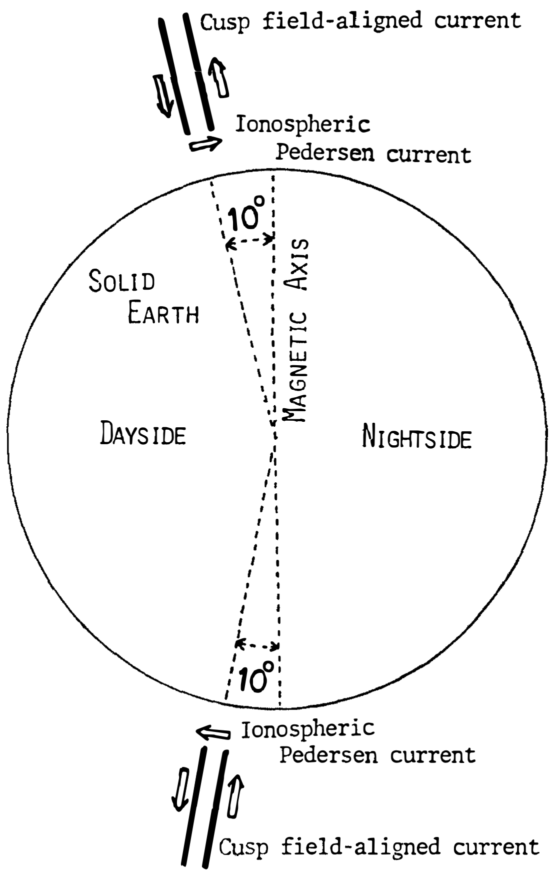

Fig. 1. Schematic diagram of a noon-midnight section of the earth seen from the dusk side. The arrows represent direction of currents when IMF B_y-component is positive. In each hemisphere, a pair of field-aligned currents flows in the cusp, and the ionospheric Pedersen current links up with it. When IMF B_y-component is negative, the direction is reversed.

ward (dawnward) Hall current flows between them. When IMF B_y-component is negative, the directions of all these currents are reversed. The properties of the currents have been summarized (PRIMDAHL and SPANGSLEV, 1981; KAMEI *et al.*, 1983) as follows: (1) The direction of the B_y-dependent current is antisymmetric to the equatorial plane, whereas the directions of the other field-aligned currents in the auroral zone are symmetric to the equatorial plane. (2) The direction of magnetic deviation in the cusp caused by a pair of B_y-dependent cusp field-aligned sheet currents is the same as that of IMF, as if IMF has penetrated into the cusp with its direction preserved. (3) The magnitude of this magnetic deviation in the cusp is estimated several tens as large as that of IMF B_y-component.

There have been proposed several models of the B_y-dependent field-aligned current, but all of them are steady state models. We will propose a transitional model in this paper.

2. Conditions to Construct a Transitional Model

2.1. *Two models of quasi-steady state*

A global configuration has been constructed which is consistent with the properties mentioned above. There is a single steady-state current system which shields out IMF B_y-component from the magnetosphere except for the cusp as shown in Fig. 2a.

It flows along the magnetopause-boundary layer; the B_y-dependent pair of field-aligned currents observed in the cusp is also a part of this global current system. The surface along which the global current system is expected to be formed is supposed to be a good conductor. There are two steady state models which agree with this configuration. One is by D'ANGELO (1980), and the other is by PRIMDAHL and SPANGSLEV (1981).

The directions of the currents at the dayside are the same between these two models. But we can point out differences between the two models. Consider a case where this conductive surface is closed at the nightside of the earth as shown in Fig. 2b. The direction of the global current system in the model of D'ANGELO is the same at the nightside as at the dayside because of the constant voltage generator which is maintained by the reconnection, so we can call this current system "poloidal". That of PRIMDAHL and SPANGSLEV is the opposite between the dayside and the nightside because of the constant current induction which is maintained by magnetic shielding, so we can call this current system "toroidal". In other words, the current of D'ANGELO's is sensitive to the product of interplanetary electric field and conductivity of the surface, whereas that of PRIMDAHL and SPANGSLEV's is sensitive to IMF. If the poloidal model is valid, we can estimate the average conductivity from the total

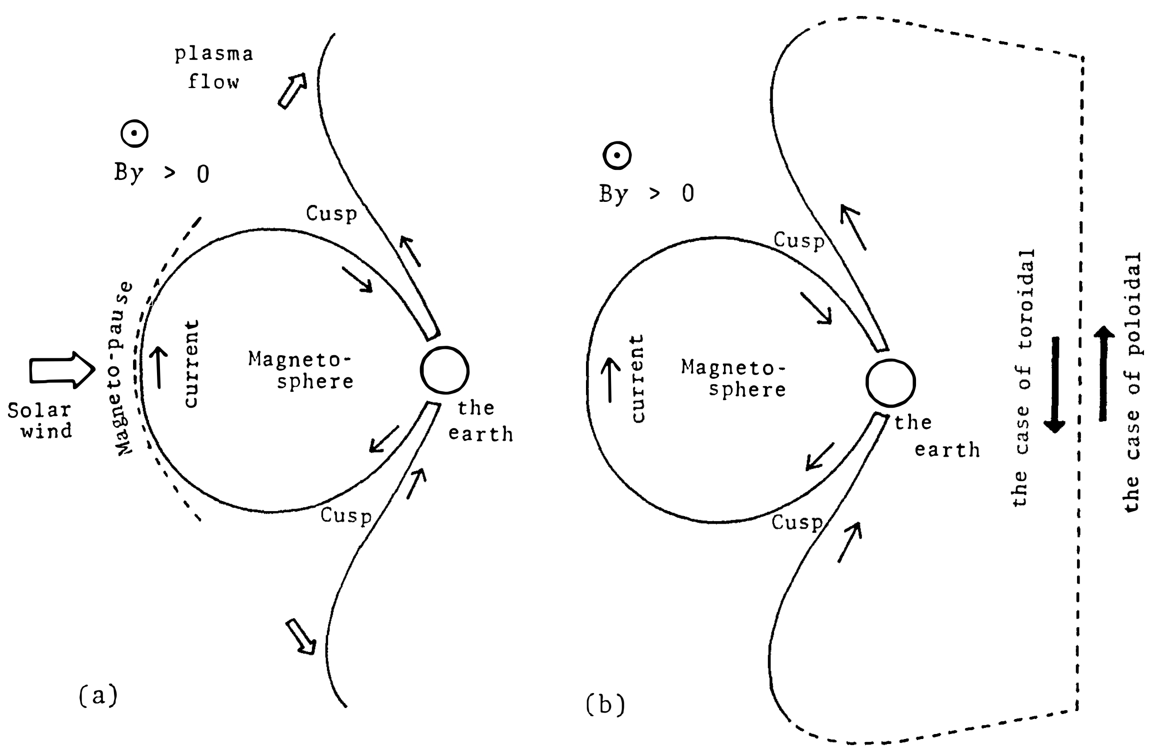

Fig. 2. Schematic diagram of a steady state model when IMF B_y-component is positive. (a) There is a global current system (light solid arrows) which is partly composed of the B_y-dependent cusp currents; this current flows also along the magnetopause-boundary layer. (b) If this current system is fundamentally 'poloidal', the direction of the nightside current (heavy solid arrow) is the same as the dayside current. If 'toroidal', the directions are opposite between the dayside and the nightside.

current observed in the cusp, whereas if the toroidal model is valid, we can estimate the ratio of the total cusp current to the global shielding current flowing along the magnetopause-boundary layer. In the poloidal model, the idea of the reconnection is used as a mechanism by which the induced charges are carried away, and without the reconnection, interplanetary electric field is shielded out by the induced charges.

2.2. *A transitional model*

The Maxwell's equations and the kinetic equations are uncoupled in steady-state models. But in transitional models, both systems of equations should be combined so as to know the propagation or the penetration of the electromagnetic information into the magnetosphere. A possible quasi-steady state may be achieved as a certain state of transitional model, *i.e.* if the temporal variation of the transitional state is very slow, the system can be thought of as a quasi-steady state while the system is still proceeding to the final state which is different from the present state. We will make up a transitional model such that accounts for the toroidal current model as a possible quasi-steady state model.

To begin with, we will consider conditions necessary to construct a possible transitional model. (1) The cusp field-aligned current (it is a pair of oppositely directed currents) should be a part of the global current system which is linked to the magnetopause current as suggested by D'ANGELO (see Fig. 2), *i.e.* we consider that the y-directed magnetic deviation between the pair of field-aligned currents is a consequence of direct penetration of IMF B_y-component. (2) Throughout the penetration of IMF B_y-component into the cusp, the orientation of the magnetic deviation should be preserved. (3) Even if other parameters in the solar wind are constant, the cusp field-aligned current should be generated depending on IMF. (4) It is IMF B_y-component rather than B_z-component that generates this current system. (5) Seasonal effect should be explained such that the field-aligned current is stronger in the summer hemisphere than in the winter hemisphere (FUJII *et al.*, 1981).

We will make use of several assumptions for simplification. First, a current which flows on the solar sector boundary sweeps wrapping the earth and closes behind the earth soon after it has passed. Secondly, the induced charges by the interplanetary electric field do not go away from the earth's magnetosphere. In other words, we will not think of the reconnection as a mechanism to carry away the charges which should shield the poloidal electric field in the solar wind.

3. Simple Media

We consider the entrance of IMF B_y-component, *i.e.* we consider the propagation or penetration of the shielding current system given by eq. (1).

$$\int \boldsymbol{J}\cdot \mathrm{d}\boldsymbol{S}+\int \frac{\partial \boldsymbol{D}}{\partial t}\cdot \mathrm{d}\boldsymbol{S}=\int_C \frac{\boldsymbol{B}}{\mu}\cdot \mathrm{d}\boldsymbol{l}\,, \tag{1}$$

where, $\boldsymbol{J}$ is the conduction current, $\partial \boldsymbol{D}/\partial t$ is the displacement current, $\boldsymbol{B}$ is the magnetic field, μ is the magnetic permeability, and C is the closed curve which contains the two representative points; one behind the solar sector boundary (A in Fig. 3), and the other in the magnetosphere where B_y is zero (A′ in Fig. 3). In the high-altitude magnetosphere, especially near the magnetopause-boundary layer, it is not clear how kinetic equations of plasma motion are. Thereupon we substitute a simple relation apposite to consideration of the B_y-dependent current.

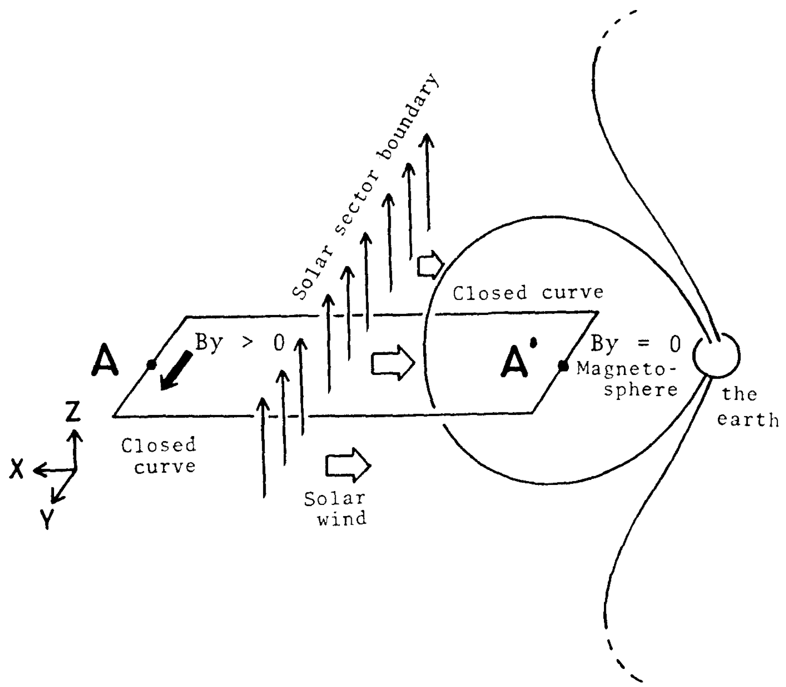

Fig. 3. Closed curve in eq. (1) is shown. It connects the points A in the solar wind and A′ in the magnetosphere, beyond the current surface (light solid arrows) on the solar sector boundary. Y-component of magnetic field (heavy solid arrow) is positive at A and zero at A′.

First, we substitute a dielectric medium for the interplanetary medium. In this case, the medium does not move, and polarization currents flow in place of conduction currents. This substitution is possible because we do not think of the dependence of the cusp current on the solar wind dynamic pressure and the interplanetary electric field. The velocity of plasma flow represents that of propagation of information of the y-directed magnetic deviation. The dielectric constant is given by eq. (2).

$$\varepsilon=\left(\frac{c}{u_0}\right)^2\cdot\varepsilon_0\,, \qquad (2)$$

where ε is dielectric constant of the interplanetary medium, ε_0 is that of vacuum, c is the velocity of light, u_0 is the solar wind velocity. Therefore, any electromagnetic transversal wave propagates with velocity u_0. When we replace the convenient sham medium by the real interplanetary medium after studies, we must exchange the currents and add plasma motion. We also use a dielectric medium where the solar wind plasma flows with balk velocity, u. For example, in the entry layer which was found by PASCHMANN *et al.*, magnetosheath plasma flows in (PASCHMANN *et al.*, 1976; HAERENDEL *et al.*, 1978). We use eq. (2) in such regions, after substituting u for u_0 in eq. (2). In this equation, increasing ε represents the plasma deceleration.

Secondly, we assume conductive media at the magnetopause-boundary layer except near the entry layer, because (1) the solar wind particles, which carry the current system on the solar sector boundary, do not enter more deeply, so that the magnetic shielding current (eq. (1)) remains there stationary; (2) the direction of the magnetic shielding current is parallel to the field lines, especially in the case of tangential discontinuity. It is noticed that penetrations of field-aligned current systems across the field lines in magnetohydrodynamics (MHD) media are the same as inductions in conductors. The ionosphere is also assumed to be a conductive medium.

Thirdly, we assume a MHD medium in the mid-altitude cusp between the ionosphere and the entry layer; and we adopt the idea of frozen-in condition there. Therefore, the magnetic deviation accompanies the earth's plasma motion in the mid-altitude cusp. We do not use the MHD frozen-in conditions, however, in the high-altitude cusp where the solar plasma flow is not parallel to the y-directed magnetic deviation (B_y-deviation).

4. A Possible Transitional Model

Here we will consider the solar sector boundary passage through which IMF B_y-component changes from zero to some value without changing other parameters. When the traveling current system on the solar sector boundary has touched the magnetopause, a stationary current is formed there except near the entry layer through which solar plasma flows across the geomagnetic field. In the entry layer, the current system also travels with plasma velocity and a new stationary current is formed at low latitude side of the entry layer as an extension of the magnetopause current. When the solar sector boundary reaches the high-altitude cusp, the solar plasma cannot enter more deeply because of the earth's increasing plasma pressure and/or the increasing geomagnetic fields, and the solar plasma flows away toward the plasma mantle. Thus, the magnetic shielding current remains also at the poleward side of the high-altitude cusp, so that the direction of this current is parallel to the geomagnetic field. Thereafter, the current system accompanied by the B_y-deviation propagates independently of the plasma flow. Taking into account of inertia of the particles (ion and electron) which compose the current, the penetration of the B_y-deviation, *i.e.* that of the shielding current system, occurs mainly along the geomagnetic field lines.

Once the B_y-deviation which is perpendicular to the geomagnetic fields is generated in the cusp, it propagates downward through the cusp along the field lines enhancing its strength, because the width of the cusp decreases at the lower altitude. Since we do not think of the induction of plasma flow or convection by viscous-like interactions, and since plasma flow is independent of the magnetic deviation near the high-altitude cusp, only the magnetic deviation descends without plasma motion parallel to the solar plasma flow. As it descends downward, the MHD frozen-in condition becomes satisfied in the mid-altitude cusp, and Alfvén wave is formed accompanied by plasma convection perpendicular to the solar plasma flow (*cf.* Section 5).

Since both the cusp field lines and the magnetic deviation are tangential to the surface of the cusp tube at both equatorward side and poleward side of the cusp, rotational type discontinuities with weak normal components of the magnetic field are formed there. A rotational type discontinuity with very weak normal component of magnetic field is quasi-stationary and strongly related to field-aligned currents as shown in Fig. 4. Thus a pair of field-aligned currents is generated on the trail of the wave front of the propagating B_y-deviation at the equatorward and poleward sides of the cusp.

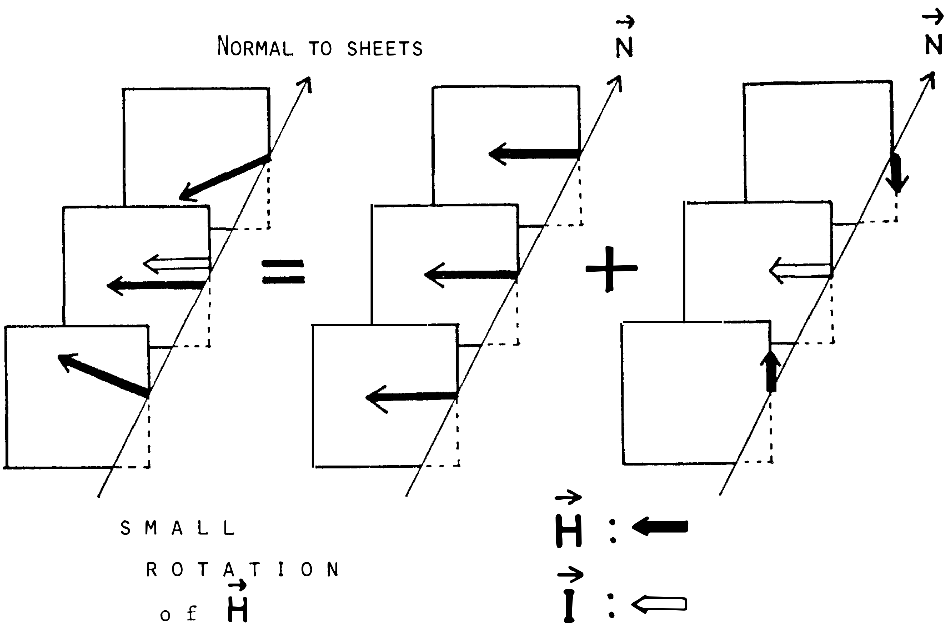

Fig. 4. Hodogram of rotational discontinuity. The normal component of the magnetic field is not shown because it is constant. Rotation of tangential component of the magnetic field in the discontinuous plane means that the equivalent current must be parallel to the tangential component of the magnetic field. When the sense of the rotation is reversed, the current must be antiparallel.

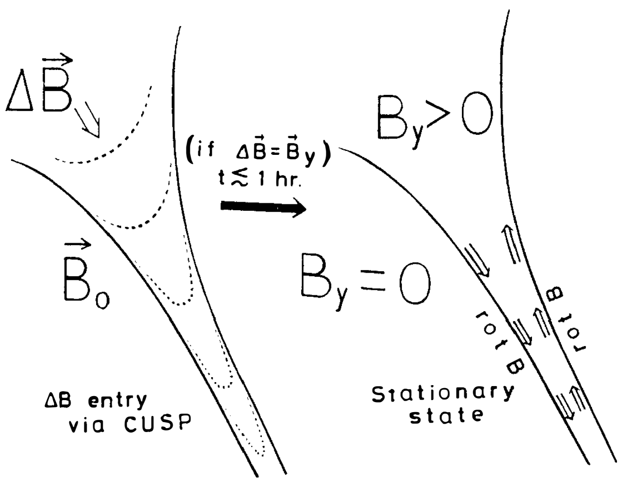

Fig. 5. Schematic diagram of the entrance of IMF B_y-component. Once magnetic deviation perpendicular to the main field is generated in the high-altitude cusp, the disturbance propagates along the cusp field lines onto the ionosphere. A pair of field-aligned currents is generated on the trail of the propagation at both equatorward and poleward sides of the cusp.

Consequently, deformation of the shape of B_y-shielding area by descent of B_y-shielding current along the cusp field lines generates the cusp field-aligned current. We can regard the descending B_y-shielding current as the wave front of propagating

B_y-deviation as shown in Fig. 5. When the shielding current system has touched the ionosphere, we can suppose that the information of B_y-deviation has touched the global good conductive surface everywhere in the dayside. Here, we can suppose the magnetic deviation above the ionosphere being enhanced by the ionospheric Pedersen current. Then a quasi-steady state current system which is essentially toroidal may be seen on the global conductive surface. The surface is composed of the magnetopause-boundary layer, low-latitude side of the entry layer and the cusp, cusp ionosphere, high-latitude side of the cusp and the entry layer, and the plasma mantle or the magnetopause.

5. Discussion

A transitional model has been proposed selfconsistently. According to this model, the cusp current is a part of a global toroidal current system which shields out IMF B_y-component from the magnetosphere except for the cusp. In other words, IMF B_y-component enters directly via the cusp. The toroidal current system must flow originally along the magnetopause-boundary layer only, but since the plasma flow can go through there easily at the high-latitude magnetopause, the current enters inside there. In the high-altitude cusp, the magnetic deviation perpendicular to the geomagnetic field descends independently of the plasma flow. In the mid-altitude cusp where the MHD frozen-in condition is satisfied, the magnetic deviation forms the Alfvén wave together with a pair of field-aligned currents on the trail of this wave at the equatorward and poleward sides of the cusp. When the propagation becomes slow at the ionosphere, we observe the magnetic shielding current system as a quasi-steady state.

It should be noticed that there is the plasma convection in the cusp because of frozen-in condition. In the mid-altitude cusp, the B_y-deviation moves plasma according to eq. (3) which is the relation for Alfvén wave.

$$\boldsymbol{v} = -\frac{\boldsymbol{b}}{\sqrt{\mu\rho}}, \tag{3}$$

where ρ is the density of the plasma, μ is the magnetic permeability, $\boldsymbol{b}$ is the magnetic deviation and $\boldsymbol{v}$ is the plasma motion. According to this, the direction of the plasma convection generated in the cusp is parallel to that of the ionospheric electron convection and is perpendicular to that of the inflow of the magnetosheath plasma in the entry layer.

We considered the entrance only of magnetic field, and ignored electric potential which is associated with the reconnection; *i.e.* we considered the entrance of the toroidal current system. But restricting to the dayside, this transitional description is also applicable to the entrance of the poloidal current system. For example, if it is the MHD rotational discontinuity that remained as the magnetic shielding current at the poleward side of the high-altitude cusp, plasma flows across this discontinuous surface, and the MHD dynamo maintains the cusp current, such as the poloidal case of Fig. 2b. Thus the poloidal electric field enters accompanied by the toroidal current system.

If the entrance of magnetic field is more effective to generate the cusp field-aligned

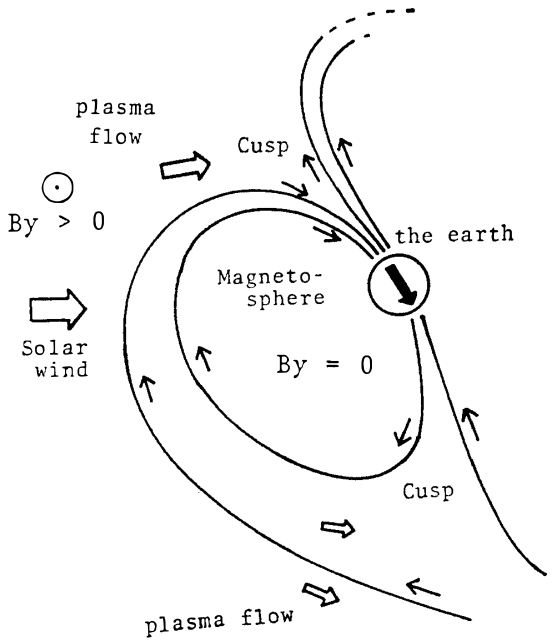

Fig. 6. Schematic diagram of the magnetosphere viewed from the dusk side. The northern hemisphere is summer, and the IMF B_y-component is positive. The global current system does not enter in the winter hemisphere sufficiently.

current than that of electric potential, we observe the cusp current as a pair of field-aligned currents, and the field-aligned current is less sensitive to the ionospheric Pedersen conductivity. If the entrance of electric potential is more effective than that of magnetic field, we observe that the field-aligned current at high-latitude side of the cusp is more dense than at low-latitude side, and the field-aligned current is more sensitive to the ionospheric Pedersen conductivity.

We can propose another reason for the seasonal effect. When the magnetic pole is located on the nightside, the solar plasma in the entry layer does not enter sufficiently into the high-altitude cusp, because the distance between the magnetosheath and the high-altitude cusp is too long (see Fig. 6). So, the magnetic shielding current does not arrive at the high-altitude cusp. Thus we can expect that the rate of entrance of the shielding current system in the summer hemisphere is different from that in the winter hemisphere.

Acknowledgments

The author is deeply grateful to Dr. T. ARAKI (Data Analysis Center for Geomagnetism and Spacemagnetism, Faculty of Science, Kyoto University), for helpful discussions and critical reading of this manuscript. He has been benefited by Mr. T. KAMEI with valuable comments and discussions. Thanks are also due to many of our colleagues for their advices.

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(Received May 1, 1984; Revised manuscript received October 30, 1984)