Ionospheric Plasma Convection Observed by HF Radar Network in the Northern Polar Region

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The space weather forecast is getting more and more important issue for the operations of the spacecrafts and telecommunication facilities. Among several important research subjects in the space weather, we studied the transmission mechanism of the electromagnetic energy into the inner magnetosphere and to low latitude ionosphere, using radar and magnetometer networks. We report in this article that the ionospheric plasma convection in the polar region is closely related with magnetic disturbances at the geomagnetic equator and in the inner magnetosphere. With these observational facts, we emphasize a crucial role of the ionosphere in transmitting the electromagnetic energy to the space.

Keywords
Ionospheric convection, Convection electric field, DP2 current, Magnetosphere-Ionosphere coupling system

1 Introduction

In light of recent advances in space-related endeavors, the study of space weather as a practical science of prediction is becoming increasingly important. One major issue to be resolved to enable practical space weather forecasting is the question of the mechanism of the transmission of electromagnetic energy into the inner magnetosphere, where radiation belts and ring currents generated during geomagnetic storms are present, and also into the low-latitude and equatorial ionosphere, areas that greatly affect the positioning precision of GPS satellites. Electromagnetic energy is produced in the outer magnetosphere as a result of interactions between the solar wind and the magnetosphere, but although several models have been proposed, the means of this energy's transmission into the inner magnetosphere and into the low-latitude ionosphere remains unclear at present.

Significant variations of the large-scale convection of plasma in the magnetosphere are caused by variations in the dynamic pressure and in the interplanetary magnetic field (IMF). The electric field that generates the magnetospheric convection induces electric currents that flow along the magnetic field lines into the polar ionosphere, where these currents drive the ionospheric plasma convection. Accordingly, it should be possible to monitor the energy influx from outer space by observing plasma convection in the polar ionosphere. To this end, a high-frequency (HF) radar network in the polar region called SuperDARN (Super Dual Auroral Radar Network) was launched in 1995, and this network has since played an important role in a range of space-weather monitoring efforts. Thirteen institutes of 11 countries are currently participating in the SuperDARN project, which operates 11 HF radars in the northern hemisphere and 7 HF radars in the southern hemisphere. The convection pattern of the polar ionosphere exhibits complex variation, and is dependent on the direction of the IMF. A single SuperDARN radar allows this convection to be observed in a fan-shaped region of 3,000 km × 54° with a spatial resolution of 45 km and a temporal resolution of either 1 or 2 minutes.

The waveguide consisting of the ground and the conductive ionospheric E region plays a vital role in the transmission of electromagnetic energy into the middle-to-low latitudes and the equatorial ionosphere [Kikuchi et al., 1978]. Moreover, since the middle-latitude ionosphere is coupled with the inner magnetosphere by magnetic field lines, it may be possible that the convection electric field transmitted to the polar ionosphere from the magnetosphere is transmitted to the inner magnetosphere via the middle-latitude ionosphere. In the present paper, data obtained by the SuperDARN radar network, magnetometer networks (INTERMAGNET, IMAGE, MACCS, etc.), and satellites is employed to investigate the coupling between the polar and equatorial ionospheres and between the polar ionosphere and inner magnetosphere, in order to verify the scenario set forth above.

2 Polar ionospheric plasma convection and the DP2-type ionospheric electric current system

The electromagnetic energy that drives the magnetospheric plasma convection flows into the magnetosphere through the interactions between the IMF and the geomagnetic field at the dayside magnetopause [Dungey, 1961]. In the Dungey model, the magnetic flux, which is generated by the magnetic reconnection of the IMF and the geomagnetic field, is carried through the polar cap of both hemispheres to the magnetotail. These magnetic field lines, which have been separated into the northern and southern hemispheres, meet again at the equatorial plane of the magnetotail and reconnect, and the closed magnetic field lines return toward the Earth. This model assumes an open magnetosphere in which the IMF and the magnetic field of the magnetosphere reconnect, and offers a simple conceptual explanation for the penetration of the magnetic field and particles of the solar wind into the magnetosphere. Thus, this model has received wide support to the present day as an established explanation of convective forcing.

On the other hand, the magnetospheric electric field is carried along the Region-1 field-aligned current (R-1 FAC) and transmitted to the polar ionosphere by Alfven waves [Southwood and Kivelson, 1991; Iijima, 2000]. The R-1 FAC flows downward (flowing into the ionosphere) on the dawn side and upward on the dusk side, and is distributed on the higher latitude side of the auroral zone [Iijima and Potemra, 1976]. The electric field applied to the ionosphere drives the plasma convection in the polar ionosphere by the E × B drift, while simultaneously generating a twin-vortex Hall current centered on the foot of the R-1 FAC. This is referred to as the DP2 electric current system [Nishida et al., 1966]. Since the Hall current corresponds to the E × B drift of electrons in the ionospheric E region, the DP2 current will flow in the direction opposite to the plasma convection of ionospheric F region and will have the same pattern, if the ionospheric electric conductivity is uniform. Furthermore, since the DP2 current is carried to the dayside middle latitudes and to the geomagnetic equator, coherent magnetic field variations will be observed at high latitudes and the geomagnetic equator [Nishida et al., 1966].

Araki [1977] analyzed magnetic field variations having temporal scales of 1-2 minutes observed on the ground and associated with a sudden increase in solar wind dynamic pressure (Preliminary Reverse Impulse; PRI), and proved that these variations occur simultaneously in the polar region and the geomagnetic equator, with a precision of 10 seconds. It was suggested that the PRI electric field, which is generated as a result of compression of the

Table 1 *Examples of geomagnetic disturbances caused by DP2 electric currents expanding from the polar to equatorial ionosphere*

Authors	Year	Phenomena	Period	Driving force
Araki	1977	PRI of geomagnetic sudden commencement	1-2 minutes	Solar wind dynamic pressure
Kikuchi et al.	1996	DP2 geomagnetic field variation	Several tens of minutes to 1 hour	Interplanetary magnetic field
Motoba et al.	2003	Global PC5 geomagnetic pulsation	2-10 minutes	Solar wind dynamic pressure

magnetosphere by the sudden increase in solar wind dynamic pressure, is transmitted to the polar ionosphere accompanied by the field-aligned currents, from which it propagates instantaneously to the equatorial ionosphere to produce the equatorial PRI. Kikuchi et al. [1978] showed that such propagation of the electric field to the equator may be explained by the zero-order TM mode of the waveguide consisting of the Earth and the ionospheric E region. The simultaneous occurrence of the PRI was the first proof provided by observation that an electromagnetic energy coupling system is formed by the ionosphere from the polar to the equatorial regions.

Since the study by Araki [1977], simultaneous occurrence of magnetic field variations has been revealed in the polar and equatorial regions, on time scales of several minutes to an hour, induced by the IMF or by the dynamic pressure of solar winds (Table 1). Although the phenomena in Table 1 have different temporal and spatial scales, they are all induced by DP2-type ionospheric electric currents. The magnetic field variations in the high latitudes and the geomagnetic equator are caused by the Hall current and Pedersen current, respectively. In other words, the field-aligned currents entering the polar ionosphere from the magnetosphere are transmitted to the geomagnetic equator, which means that there is an influx of electromagnetic energy to the equator.

Next, we will describe the temporal and spatial characteristics of the polar ionospheric plasma convection which corresponds to the DP2 current. As seen in Figure 1(a), the geomagnetic X and Y components of Resolute Bay (RES; corrected geomagnetic latitude: 83.56˚, 1120 MLT at 1840 UT) located in the dayside polar cap on Nov. 17, 1996 and the X component of Ancon (ANC; corrected geomagnetic latitude 3.05˚, 1350 MLT at 1840 UT) near the geomagnetic equator in Peru on the same day began to display a synchronized quasi-periodic variation pattern for approximately 30 minutes from 1839 UT (solid vertical line). The WIND satellite also observed a similar periodic variation in the Bz component of the IMF. Furthermore, the geomagnetic Y components, which were located near 12 MLT at 1840 UT, of the magnetometer observation networks CANOPUS and MACCS [Fig. 1(b)] covering the region from the polar cap to the subauroral zone, and the geomagnetic Y component in Greenland [Fig. 1(c)] located at 17-21 MLT at 1840 UT, both displayed inverse-patterned magnetic field variations. On the other hand, the amplitude of the observed fluctuations in the magnetic field was extremely small at San Juan (SJG; corrected geomagnetic latitude: 28.91˚, 1430 MLT at 1840 UT) in the low latitudes [Fig. 1(a)]. The characteristics of the DP2-type electric currents include such global-scale synchronicity in magnetic field variations and latitudinal dependence of amplitude (with decreasing amplitude from the higher to lower latitudes and anomalous amplification on the dayside dip-equator), in addition to the twin-

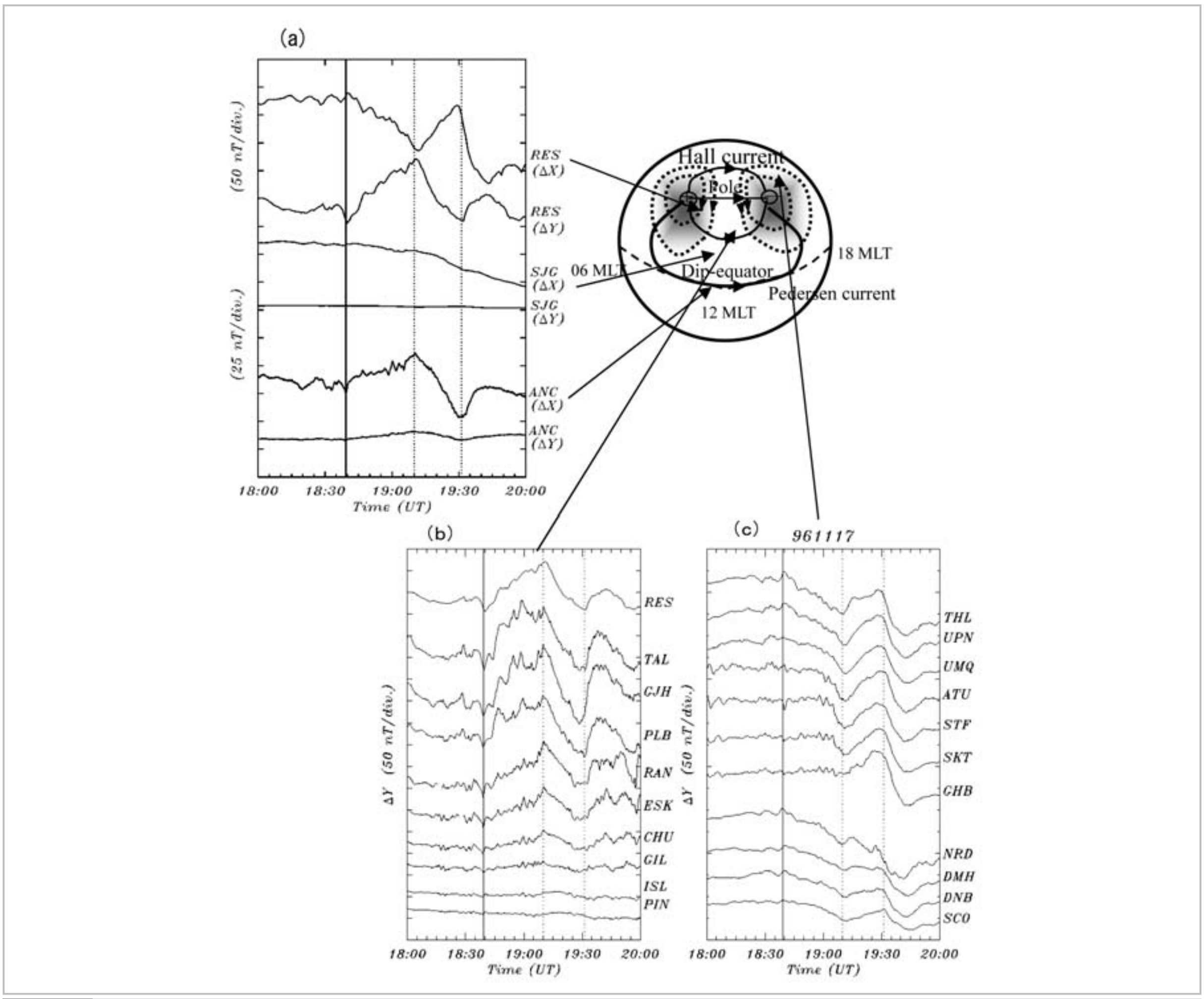

Fig. 1 DP2 geomagnetic field variations observed from the polar to equatorial regions

(a) geomagnetic X and Y components at the polar cap and the dayside low-latitude region and geomagnetic dip-equator (1120-1430 MLT at 1840 UT); (b) geomagnetic Y components of the magnetometer chain from the polar cap to the subauroral zone (MACCS, CANOPUS) (1120-1220 MLT at 1840 UT); and (c) geomagnetic Y component of the Greenland magnetometer chain (1550-1635 MLT at 1840 UT). [Hashimoto and Kikuchi, 2005a]

vortex pattern of the two-dimensional equivalent current distribution (see schematic diagram in Fig. 1).

Figure 2 presents the plasma velocity data for the polar ionospheric F region observed by the SuperDARN HF radar before and after the development of the DP2 current. Figs. 2(a) and (c) show velocity vectors obtained by synthesizing the line of sight velocities observed by two HF radars at Saskatoon and Kapuskasing (Canada). Figs. 2(b) and (d) are two-dimensional plasma convection maps in the polar region calculated using the potential map model of the Applied Physics Laboratory of John Hopkins University (JHU/APL; Ruohoniemi and Baker, 1998) and line of sight velocity data obtained by observation. Before the development of the DP2 current [Figs. 2(a) and (b)], a small plasma vortex was observed at the dayside geomagnetic latitude of 80-85˚. This convection vortex is a reverse convection cell generated by the electric field accompanying the NBZ field-aligned current that develops during northward IMF. Then, after the development of the DP2 current, a two-cell plasma convection develops [Figs. 2(c) and (d)]. Generally, during the southward turning of the IMF, the DP2 current system develops globally in the ionosphere, and two-cell plasma convection develops in

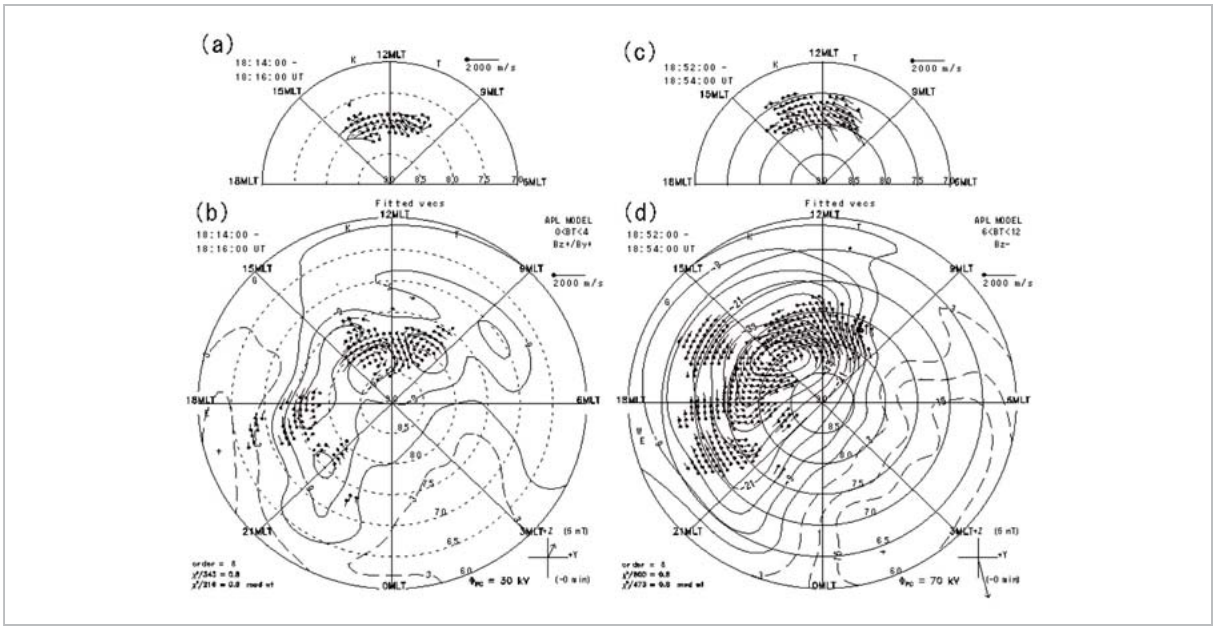

Fig.2 *Change in plasma convection pattern due to southward turning of the IMF on Nov.17, 1996*

Plasma convection pattern of the polar ionosphere (F region) observed prior to and following the southward turning of IMF observed with the SuperDARN at 1814-1816 UT (a) and (b) and 1852-1854 UT (c) and (d) on Nov. 17, 1996 [Hashimoto and Kikuchi, 2005a]. (a) and (c) Dayside plasma flow obtained by synthesizing the line of sight velocities observed by the HF radar at two sites (Saskatoon and Kapuskasing); (b) and (d) plasma flow obtained by potential map model of APL/JHU.

the polar region. The electromagnetic energy produced in the dayside magnetosphere flows into the polar ionosphere via the R-1 FACs. The resultant electric field causes the development of the two-cell Hall current and plasma convection. The magnetospheric convection electric field propagates instantly with a precision of several tens of seconds to the global ionosphere and induces the DP2 current at the dayside equator that connects R-1 FAC [Kikuchi et al., 1996].

During the development stage of the convection caused by the southward turning of the IMF, the DP2 convection electric field propagates from the pole to the equator or from the dayside to the nightside in the ionosphere within several tens of seconds [Kikuchi et al., 1996; Ridley et al., 1998; Ruohoniemi and Greenwald, 1998; Murr et al., 2001; etc.]. In contrast, it takes about 4-6 minutes for the convection pattern for the northward IMF to disappear totally in the polar cap [Hashimoto and Kikuchi, 2005a], implying that more than 4-6 minutes is required for the plasma convection in the magnetosphere to convert completely to the pattern for the southward IMF. Further, the polar cap plasma convection observed with SuperDARN is driven by the potential electric field accompanying the field-aligned currents, implying that the field-aligned current newly developed in the magnetosphere after the southward turning of the IMF coexists with the field-aligned currents of the northward IMF. These results are consistent with that of the global MHD simulation by Tanaka [2000].

The above results indicate that the magnetosphere and the ionosphere become coupled by the field-aligned currents, and that plasma convection and DP2 currents are generated in the surrounding the field-aligned currents. The field-aligned currents are mainly controlled by the direction of the IMF Bz. When the IMF turns from northward to southward, R-1 FACs begin to develop, which in turn cause the development of the DP2 current in the global ionosphere including the equator. However, in the polar ionosphere during the first 4-6 minutes, both field-aligned currents coexist, and the convection in the magnetosphere converts from a pattern of the northward IMF to that of the southward IMF more gradually. The convection electric field, which is propagated to the polar ionosphere from the magnetosphere by Alfven waves along the magnetic field lines, is carried to the middle-to-low latitude regions, and this horizontal propagation permits the transmission of energy to the entire magnetosphere-ionosphere coupling system. In this way, the ionosphere plays an important role as the energy transmission path within the entire magnetosphere-ionosphere coupling system.

3 Synchronicity of convection development in the ionosphere and the inner magnetosphere

The magnetosphere is separated into several domains according to plasma density and temperature and therefore features strong anisotropy with respect to the geomagnetic field. The ionospheric E region constituting the Earth-ionosphere waveguide has sufficient electrical conductivity so that its latitudinal non-uniformity does not have a large effect on the electromagnetic energy transmission to the low latitudes and equatorial regions. We consider polar-equatorial ionospheric coupling to be important in the transmission of electromagnetic energy to the inner magnetosphere, and have investigated the relationship between polar ionospheric convection and magnetic field variations in geostationary orbits. The delay in initiation of these variations will allow us to estimate the propagation mode of the energy driving the inner magnetospheric convection.

Figure 3 shows the polar ionospheric convection patterns during northward IMF (a) and southward IMF (b). Using the potential map model and the observation data from 6 SuperDARN HF radars, two-dimensional plasma convection patterns have been calculated for data at 1056-1058 UT and 1106-1108 UT on March 26, 1998. Fig. 3(a) shows the four-cell pattern during northward IMF, and (b) shows the two-cell pattern during southward IMF. On the other hand, magnetic field observations in the polar cap show that the DP2 magnetic field variation is initiated at 1100 UT (top panel of Fig. 4), and that the polar ionospheric convection begins to intensify at that point. However, the pattern does not immediately take a two-cell structure, and after approximately 6 minutes from 1100 UT, the convection switches from a four-cell pattern to a two-cell pattern [Hashimoto and Kikuchi, 2005b].

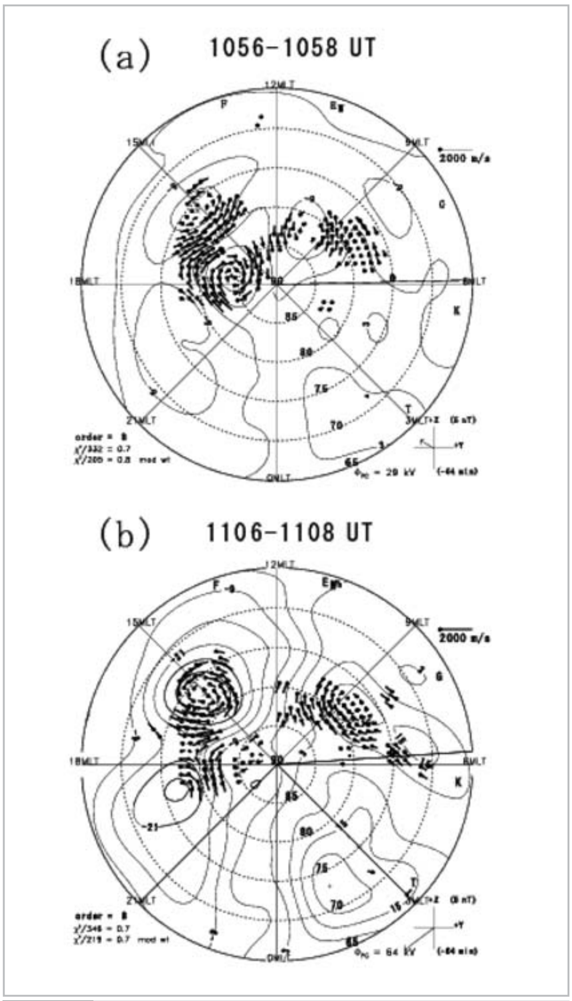

Fig.3 *Plasma convection pattern observed by the SuperDARN network in the polar ionosphere (F region) at (a) 1056-1058 UT and (b) 1106-1108 UT on March 26, 1998 (Hashimoto and Kikuchi, 2005b). The APL/JHU potential map model was used for the plot*

In order to compare the development of the polar ionospheric convection and the onset of plasma sheet thinning caused by the development of magnetotail convection, the DP2 mag-

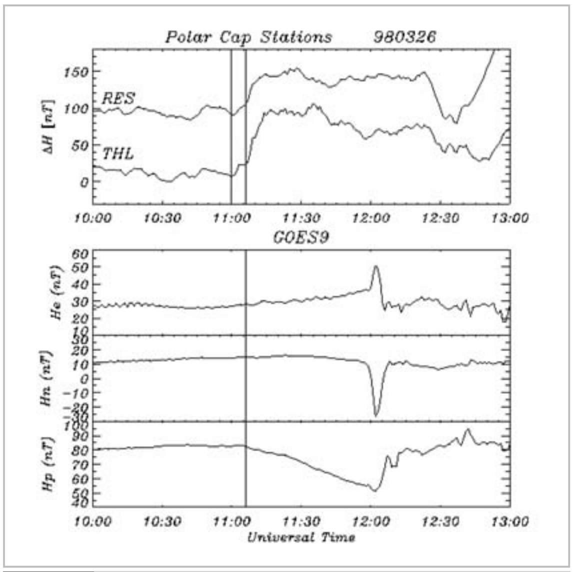

Fig.4 *The geomagnetic X component in the polar cap (a) and the three magnetic field components observed with the GOES-9 satellite (b)*

The DP2 electric current system begins to develop at 1100 UT [Hashimoto and Kikuchi, 2005b]. Then, at 1106 UT, the GOES-9 satellite observes a decrease in the Hp component, indicating the onset of thinning in the magnetotail.

netic field variations in the polar cap and the three magnetic field components observed by the GOES-9 satellite in the geostationary orbit are presented as shown in Fig. 4. The first vertical line in the top panel of Fig. 4 shows that the polar cap magnetic field begins to increase at 1100 UT and increases further at 1106 UT. The magnetic Hp component observed by the GOES-9 satellite in the geostationary orbit (bottom panel of Fig. 4) begins to decrease at 1106 UT. The GOES-9 satellite is positioned at 0020 MLT at 1100 UT, and so the decrease in the Hp component indicates the onset of stretching of the magnetotail (plasma sheet thinning). This is believed to be a result of the enhancement of plasma convection in the magnetotail, which increases plasma pressure in the geostationary orbit.

The DP2 current system develops at 1100 UT, and then at 1106 UT, after 6 minutes have elapsed, the plasma convection switches from a four-cell pattern into a two-cell pattern [Fig. 3(b)]. The plasma sheet thinning initiated at the position of the GOES-9 satellite indicates that the development of convection on the nightside inner magnetosphere occurs when the two-cell convection becomes dominant. As stated in the previous section, the DP2 current system propagates horizontally at the speed of light, together with the electromagnetic energy. Thus, it is believed that this current system propagates instantaneously at 1100 UT to the dayside and nightside middle-to-low latitude regions from the polar cap [thick solid line in Fig. 4(a)]. However, the remnant four-cell convection pattern due to the northward IMF suppresses the intensity of the inner magnetospheric convection electric field, and so the onset of plasma sheet thinning is delayed to 1106 UT, at which point convection switches to a two-cell pattern.

Ever since the proposal of Dungey[1961]'s magnetospheric convection model, it has been believed that convection is driven by the magnetic flux generated by the reconnection of the solar wind magnetic field and the geomagnetic field, which is carried to the magnetotail. Dungey's model was originally proposed to explain the pattern of the polar ionospheric electric current system. Nearly 30-50 minutes is required for the magnetic flux to be transported to the magnetotail and to reach the inner magnetosphere. Therefore, this model conflicts with the observation noted above — i.e., simultaneous development of ionospheric convection over a wide range and of the ionospheric electric current induced at the equator.

In terms of the development of the convection electric field in the polar ionosphere associated with solar wind magnetic field variations, discussions by Ridley et al. [1999] and Lockwood and Cowley [1999] triggered a series of debates from the two different standpoints of fast and slow propagation mechanisms, as described below.

(1) Convection electric fields on the dayside and nightside ionosphere begin to develop simultaneously within 1 minute (based on observation by magnetometer and HF radar networks) [Ridley et al., 1998; Ruohoniemi and Greenwald, 1998; Murr et al., 2001, etc.]

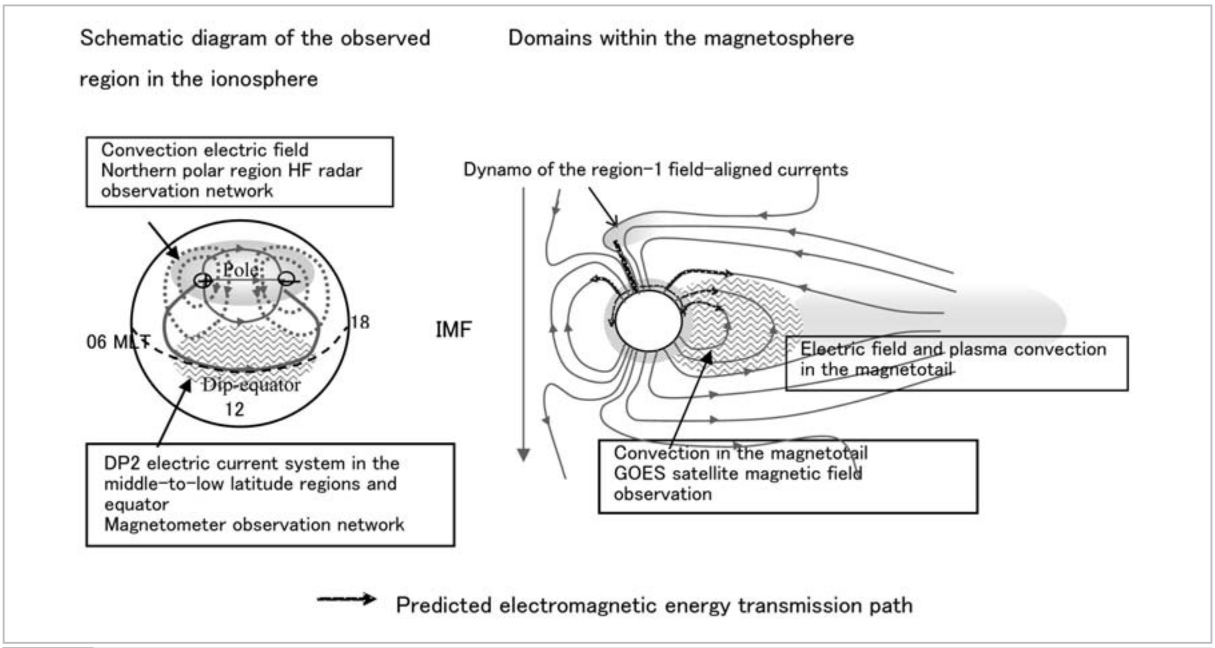

Fig.5 *Electromagnetic energy transmission path within the magnetosphere-ionosphere coupling system deduced from the characteristics of the polar-to-equatorial electromagnetic coupling*

(2) The two-cell ionospheric convection spreads from the dayside to the nightside over a period of 10 minutes (based on local magnetometer and radar observations) [Etemadi et al., 1998; Todd et al., 1988, etc.]

The fast propagation is attributed to magnetoacoustic waves propagating at speeds of 1,000 km/s or higher [Ridley et al., 1999; Murr et al., 2001; Slinker et al., 2001]. However, this theory was challenged by theoretical studies that claimed that magnetoacoustic waves propagating inside the magnetosphere could not drive convection in the ionosphere [Southwood and Kivelson, 1991; Iijima, 2000, etc.]. These debates have yet to be settled. Moreover, the subject of discussions was limited to ionospheric convection in the polar region, and so polar ionospheric convection was discussed only within the framework of conventional conceptual models, which regarded polar ionospheric convection simply as a projection of magnetospheric convection.

It is important to regard the transmission of electromagnetic energy from the pole to the equator as a unique property of the ionosphere, and to examine the role this pole-to-equator transmission plays in the transmission of energy to the inner magnetosphere and the magnetotail. In past discussions, much of the essential physical properties of the ionosphere were overshadowed by the concept of the "incompressibility" of the ionosphere. This notion of the "incompressible ionosphere" causes researchers to assume, erroneously, that the ionosphere is simply a medium through which convective motion is transmitted, completely ignoring its characteristics as a region of energy dissipation. We have attempted to reexamine the transmission of energy that drives convection in the magnetosphere-ionosphere coupling system based on the viewpoint that the incompressibility of the ionosphere is a reflection of electromagnetic energy coupling between the pole and equator and the dayside and nightside in the ionosphere.

As shown above, analysis based on data from ground-based radars and geomagnetic observations has revealed that the pole-equator ionosphere constitutes a coupling system through which electromagnetic energy is transmitted. Figure 5 shows a schematic diagram of the electromagnetic energy transmission path in the magnetosphere-ionosphere coupling system deduced from this characteristic. In this model, the magnetospheric convection electric field induces currents in the global ionosphere, and part of that energy is transmitted to the inner magnetosphere and the magnetotail via the ionosphere. We have focused on the unique properties of the ionosphere that render this a region of strong energy dissipation as well as an energy transmission path. We expect that this approach will provide strong constraints on the conditions that must be satisfied by a model of electric field transmission to the inner magnetosphere.

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