Geomagnetic Substorms with Different $\Delta D/\Delta H$ Ratios Associated with Low-Latitude Aurora on October 21, 1989

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During the severe magnetic storm on October 21, 1989, three intense substorms took place successively at 2-hour intervals in evening-midnight hours in the Western Pacific region, with the sense of (ΔD , ΔH) deviations of three geomagnetic bays associated with the substorms being (+, -), (+, + to -, +), and (-, +), respectively. The second and third bays were observed in conjunction with an unusual low-latitude aurora seen in the northern sky of Hokkaido (the northern island of Japan). In this paper, a scenario is proposed for the occurrence mechanism of these three consecutive bays, in which they are accounted for in terms not only of a local increase in the Hall conductivity in the ionospheric *E*-layer but also of a decrease in the Pedersen conductivity in the *F*-layer. A noticeable upward drift of the *F*-layer associated with the low-latitude aurora is responsible for the reduction of the Pedersen conductivity, despite an increase in the total electron content in the ionosphere.

1. Geomagnetic Bays Associated with a Low-Latitude Aurora Seen in Hokkaido, Japan

An unusual aurora was observed in the northern area of Hokkaido, Japan, during the severe magnetic storm on October 21, 1989, as reported by MIYAOKA *et al.* (1990) and KUWASHIMA *et al.* (1990). Figure 1 (which is reproduced from Fig. 4(a) of the Miyaoka *et al.* paper) shows that the auroral belt shifted down to geomagnetic latitude 50° or even lower in the Far East region during the main phase of the magnetic storm.

The magnetogram at Memambetsu Observatory (43°54' N, 144°12' E; geomag. lat. 34.6°N) in Fig. 2 indicates that the following three distinct geomagnetic bays were observed in the local night of October 21, 1989, associated with three intense substorms:

	Occurrence time in 135° EMT	Maximum ΔD and ΔH deviations	
①	18.9–19.6 h during the <i>Dst</i> growth	120 nT	-80 nT
②	20.6–21.5 h near the maximum <i>Dst</i>	120 → -50	150
③	23.1–23.9 h in the recovery phase	-90	120

The simultaneous geomagnetic records at a number of middle-latitude stations were very similar to one another, not only in Japan but also in a wide range of the Western Pacific region, i.e., three large-amplitude geomagnetic bays were observed with the same (ΔD , ΔH) senses of (+, -; +, + → -, +; and -, +) with their magnitude decreasing towards the equator. It is worth reporting here that the geomagnetic bays of (+, -; +, +; and -, +) senses were also observed on the previous day (October, 20, 1989) with a difference of only 1–2 hours in local time in the Western Pacific region. The ΔD sense of + → - was once reported by TINSLEY *et al.* (1986) that such a change was observed in association with the low-latitude aurorae of July 14, 1982.

Fig. 1. (a) Location of the low-latitude aurora on October 21, 1989, derived from the EXOS-D/ATV. The trajectory of the DMSP-F9 satellite is also shown. (b) Meridional cross-section of the low-latitude aurora with view angles from Moshiri Observatory. The height of aurorae is assumed as 100–300 km for 4278 and 5577 Å emissions, and 150–500 km for 6300 Å emission (after MIYAOKA *et al.*, 1990).

Fig. 2. Magnetogram on October 21, 1989, from Memambetsu Observatory. An ssc took place at 0917 UT on the previous day with active disturbances from 10 to 20 h UT, and the H -value at 0 h UT on October 21 was about 120 nT below the pre-ssc level. The H -range of October 20–21 storm was reported to be 299 nT.

2. Remark on the Contribution to ΔD at Middle Latitudes from Field-Aligned Currents

Although ΔD observed on the ground at middle latitudes has often been attributed to the magnetic effect of field-aligned currents in the magnetosphere, we have to bear in mind that their contribution is mostly cancelled out by the Pedersen currents in the ionosphere that is directly connected to the field-aligned currents (FUKUSHIMA, 1976). Figure 3 illustrates the meridian with a field-aligned line-current of intensity I_0 flowing out of the ionosphere at colatitude θ_0 . This field-aligned current contributes to ΔD at a point P on the earth (geocentric distance r_E , colatitude θ) approximately the same magnetic field as that from a semi-infinite vertical line-current of intensity I_0 at θ_0 , i.e., $\mu_0 I_0 / \{4\pi r_E (\theta - \theta_0)\}$ eastward. If the ionospheric conductivity were uniform all over the earth, the Pedersen current density would be $I_0 / \{2\pi r_E (\theta - \theta_0)\}$ above point P , and a westward magnetic field of $\mu_0 I_0 / \{4\pi r_E (\theta - \theta_0)\}$ is produced at P to cancel the eastward magnetic field from the field-aligned current.

In actual cases, ΔD on the ground at middle latitudes is eastward with a recognizable magnitude during magnetic storms in the evening region, where a considerable amount of upward field-aligned currents flow out of the high-latitude ionosphere in the same meridian, as in the case of Fig. 3. Hence, this eastward ΔD at middle latitudes must be associated with some mechanism which reduces the shielding effect of the ionospheric Pedersen current, for example through the reduction in the height-integrated Pedersen current intensity during substorms. The mechanism for reducing the Pedersen current intensity is attributed in this paper to the reduction in the height-integrated Pedersen conductivity of the ionosphere, due to an upward drift of ions and electrons in the ionosphere under an eastward electric field, as discussed in the following sections.

Fig. 3. Meridional cross-section with an outward field-aligned line-current and associated ionospheric currents.

3. Quiet-Time Electric Currents in the Polar Region

On quiet times free from magnetic disturbances, the height-integrated conductivity of the ionosphere is slightly lower in the polar cap region in comparison with the surrounding region, as is schematically shown in Fig. 4(a). Field-aligned currents flow into the ionosphere on the morning side at the polar cap boundary and flow out of the ionosphere on the afternoon side. The primary external field-aligned currents are assumed for simplicity to peak in the dawn and dusk meridians. The corresponding electric field in the ionosphere is from the morning side to the evening side, i.e., it is westward in the night hemisphere and eastward on the dayside.

Under these circumstances, the resultant field-aligned current pattern and the equivalent current-

Fig. 4. (a) Primary field-aligned currents into and out of the ionosphere at the outer boundary of the polar-cap region. (b) Resultant field-aligned current pattern, and the equivalent current-system of the S_d^p geomagnetic field at high latitudes.

system for the S_d^p ground magnetic variation are given schematically in Fig. 4(b) after FUKUSHIMA (1975). The distortion of the current patterns in Fig. 4(b) with respect to the noon-midnight meridian is due to the Hall currents flowing in the ionosphere under the primary electric field in the dawn-to-dusk direction.

4. Conductivity Enhancement Associated with Aurora, and Its Subsequence

A polar substorm is characterized by a sudden break-up of auroras which accompanies an enhancement of the ionospheric conductivity at auroral latitudes. The geomagnetic bays on the night of October 21, 1989, in the Western Pacific region are associated with a great enhancement of the ionospheric conductivity in the evening sector at auroral latitudes expanded down to geomagnetic latitude 50° or even lower, with a bulge for the unusual low-latitude aurora; this is shown schematically in Fig. 5(a). This interpretation is based also on the aurora-TV camera snapshots by the EXOS-D (Akebono) satellite; see MIYAOKA *et al.* (1990).

Fig. 5. Consequences of the E -layer conductivity enhancement in the auroral belt with a bulge in the evening sector: (a) Region of ionospheric conductivity enhancement, (b) auroral electrojet and associated charge separation, (c) electric field on the equatorial side of the auroral belt, (d) "hole" of the height-integrated Pedersen conductivity, due to the upward drift of electrons and ions in the ionosphere, and (e) pattern of the equivalent current-system for the reduction in Pedersen conductivity and for the Hall current associated with the charge separation shown in diagram (b); ①, ②, and ③ indicate the local times of three observed geomagnetic bays.

As a consequence of the conductivity increase in the evening sector, intense Cowling currents flow westward in the region of the enhanced conductivity. These Cowling currents must be connected to the incoming field-aligned currents near midnight and outflowing ones in the evening hours, so that the field-aligned currents in the evening are greatly enhanced. At the same time, positive/negative electric charges are to be accumulated on the western/eastern end of the region of the enhanced conductivity, as schematically illustrated in Fig. 5(b), before they dissipate eventually through the Pedersen currents in the ionosphere. The associated transient electric field, shown in Fig. 5(c), produces not only an intense Hall current in the lower E -layer, but also a remarkable reduction of the Pedersen current in the ionosphere, as explained in the next section.

5. "Hole" of the Pedersen Conductivity in the Ionosphere on the Low-Latitude Side of the Auroral Belt

The transient electric field of the form shown in Fig. 5(c) will affect the height profile of the ionosphere in such a way that the eastward field will up-drift electrons and ions so as to decrease the Pedersen conductivity of the ionosphere. REDDY *et al.* (1990) reported the F -layer rise of 100–200 km at middle and low latitudes during a substorm on January 20–21, 1989, which seems to be caused by an eastward electric field of 6 ± 1 mV/m. Such a drastic F -layer rise will result in a significant decrease in the height-integrated Pedersen conductivity (100 km increase in height in F -region reduces the specific conductivity approximately by one order of magnitude). This conductivity decrease can be expected even if the total electron content in the ionosphere is increased and an E -layer ionization may take place, as in the case of February 7–8, 1986 event in the Far East reported by HE (1989). At the GAM 2.9 Session of the IAGA Vienna Assembly, there were some reports on the upward drift of the ionospheric $F2$ layer during severe magnetic storms.

We may now suppose that a big "hole" in the Pedersen conductivity will appear on the low-latitude side of the region of enhanced conductivity, as shown in Fig. 5(d). The word "hole" is used here following the naming of the "ozone hole" in the polar region. The "Pedersen conductivity hole" modifies the ionospheric current connected to the outflowing field-aligned currents in the evening region, so as to reduce the northward currents in the ionosphere (referring to Fig. 3). This effect is equivalent to superimposing on the unperturbed current-pattern an additional equivalent current-system of Fig. 5(e), which consists of the southward concentrated current in the area of reduced Pedersen conductivity, with its return currents in the surrounding region. Note here that this equivalent current is exactly in the same direction of flow as the Hall current in the ionosphere under the electric field of Fig. 5(c). Numbers ①, ②, and ③ in Fig. 5(e) indicate the estimated locations where the geomagnetic bays numbered ①, ②, and ③ in Fig. 2 were observed.

In order to interpret the D -deflection change of $+$ $\rightarrow$ $-$, it is necessary to think of a quick westward movement of the substorm centre of the second geomagnetic bay during the course of the bay. Such a movement is not at all unrealistic.

6. Concluding Remark

As discussed in the preceding section, the equivalent current-systems for the three geomagnetic bays at middle latitudes in the Pacific area from the evening to midnight hours originate from two effects, namely, an intensified Hall current in the bulge of low-latitude aurora and a simultaneous decrease in the Pedersen conductivity in the region equatorward of the bulge; the resultant current-system is shown in Fig. 5(e). It would be quite natural to surmise that the Hall conductivity increase and the simultaneous appearance of the "Pedersen conductivity hole" due to precipitating particles from the magnetosphere took place intermittently three times during 9–15 h UT (18–24 h in 135° EMT) on October 21, 1989, at nearly the same location in the coordinate fixed to the sun. The different combinations of ΔD and ΔH ($+$, $-$; $+$, $+$ $\rightarrow$ $-$, $+$; and $-$, $+$) observed at Memambetsu (and also at many other observatories in the Western Pacific area) can be explained reasonably by the earth's rotation under the external current-systems in the

ionosphere and magnetosphere surrounding the earth.

The present paper shows a qualitative scenario for interpreting the mechanism for the occurrence of three consecutive geomagnetic bays with different $\Delta D/\Delta H$ ratios recorded during the severe storm of October 21, 1989. It is necessary to conduct a more quantitative study of each process involved in this scenario. In particular, an apparent rapid westward travelling of the substorm centre during the second geomagnetic bay associated with the low-latitude aurora on October 21, 1989 must be accounted for.

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