Polar Cap Magnetic Variations and Their Relationship with the Interplanetary Magnetic Sector Structure

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The relationship between polar geomagnetic variations and the polarity of the interplanetary magnetic sectors has been studied for the quiet year 1965. It is found that during the day hours a system of ionospheric currents encircles the magnetic poles on every day. The current system may extend up to 15° from the pole but is strongest at 8°–10° invariant colatitude. The current direction as seen from near the magnetic poles is counterclockwise during interplanetary sectors with field pointing away from the sun and clockwise during toward sectors. The current strength is dependent on season, being strongest during local summer. When the magnetic pole is on the nightside of the earth, this polar cap current is absent or very weak. When the rotation of the earth brings the magnetic pole into the dayside, the polar cap current system develops, with the current being most concentrated in the part of the current system that is nearest to the noon meridian. The current increases its total intensity until the magnetic pole is rotated past the noon meridian; then the intensity decreases as the magnetic pole approaches the nightside again. The seasonal variation of the magnetic elements in the polar cap is discussed in view of the sector polarity effects. These effects introduce an important modulation of the seasonal variations of the geomagnetic polar field. The demonstration of current systems inside the polar caps encircling the magnetic poles during local day hours calls for a major revision of the generally accepted picture of polar cap geomagnetic variations. It also suggests a new framework for interpreting polar cap observations of geomagnetic and related phenomena.

The diurnal variation of the geomagnetic field components in the polar caps is traditionally considered to be simple, consisting of a rather regular sinusoidal wave in all three components. The variation of the horizontal components resembles the magnetic effects of a uniform horizontal current sheet covering the entire polar cap. This current sheet stays fixed in relation to the direction to the sun, while the earth rotates under it. Figure 1*a* shows the diurnal variation during the summer season of the north component X and of the east component Y at Resolute Bay near the northern magnetic pole. The form of the two curves is sinusoidal to within a few gammas, and their phases differ by 6 hours. The uniformity of the variation across the polar cap is illustrated by Figure 1(*b*, *c*) for four observatories in the central northern polar cap: Alert, Thule, Resolute Bay, and Mould Bay. Figure 1*b* shows that the time of maximum X is controlled by local time, i.e., the rotation of the earth, so that the current sheet stays fixed. The amplitude of the regular diurnal variation is very nearly constant over the polar cap as shown in Figure 1*c*, being larger during the summer than during the winter. Also the amplitude on disturbed days is far larger than on quiet days.

Since the westward auroral electrojet is nearest to a polar cap station in the early morning hours, an increase of the vertical component Z is then observed. In the late afternoon the eastward auroral electrojet is nearest to the station, and a depression of Z is observed. The variation of Z during a day is thus also of a regular character. The amplitude of this variation increases with increasing distance from the magnetic pole, since this brings the observing station close to the electrojets.

It is generally believed that some of the currents that close the auroral electrojets are the cause of the uniform perturbation field across the polar cap and therefore the cause of the regular daily variation of the polar field. By way of the electrojets, geomagnetic disturbances within the polar caps are tied to the substorm activity in the auroral zones. If the substorm activity is high, strong disturbances are always observed inside the polar cap. On the other hand, considerable magnetic disturbance may be observed in the polar cap even if the activity at lower latitudes is very low, showing that processes particular to very high latitudes are in effect.

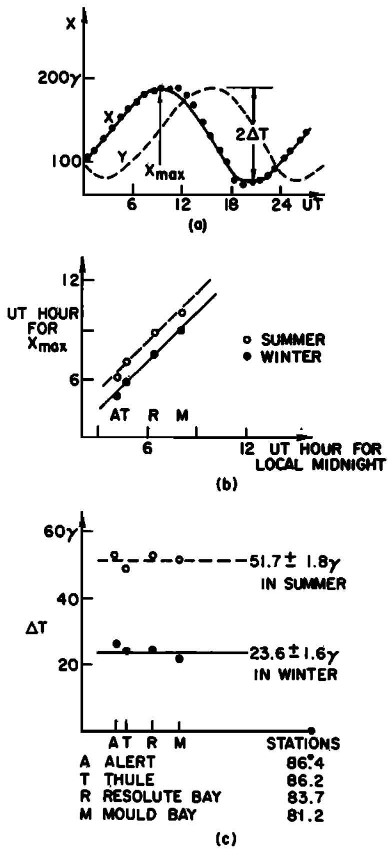

Fig. 1. Uniform average daily variation of horizontal geomagnetic field components in the polar cap. (*a*) Variation of *X* and *Y* at Resolute Bay during the summer season of 1965. The solid circles show the observed *X* variation and the solid line the smoothed *X* variation. The dashed curve shows the smoothed daily variation of the *Y* component. (*b*) Local time control of the time of observed maximum value of the north component for four northern polar cap stations. (*c*) Uniformity of the amplitude of the daily variation of the horizontal components. The approximate invariant latitude for the four stations used is also given.

The cause of the polar cap disturbances is not well understood within the frame of traditional concepts. It is the purpose of this paper to present a unified view of the large-scale features of polar cap disturbances.

The special polar cap disturbances differ from auroral latitude activity in several important ways, the most prominent being that auroral latitude activity peaks at midnight, whereas polar cap disturbances are most prominent around noon. The polar cap disturbances are usually described as being irregular without distinct patterns, so that they cancel out when several days are averaged; in this way the average daily variation takes on its simple form as described above. However, *Svalgaard* [1968, 1972] and independently *Mansurov* [1969] found a regularity in the polar cap disturbances related to the direction of the interplanetary magnetic field. When the earth is immersed in an interplanetary magnetic sector [*Wilcox,* 1968] with field directed away from the sun, daytime disturbances are observed at very high latitudes that are directed dominantly away from the earth. When the earth is within a toward sector, the disturbance field is directed toward the earth in both polar caps. A recent review of this effect has been given by *Wilcox* [1972].

This relationship between the interplanetary magnetic field (IMF) polarity and the daytime polar cap disturbances is so distinct even on individual days that it has been possible to infer the IMF polarity on a day by day basis [*Friis-Christensen et al.*, 1971; *Svalgaard,* 1972]. A closer inspection of the few days of disagreement between the inferred field polarity and the field polarity observed with spacecraft showed [*Friis-Christensen et al.*, 1972] that on most of such days the direction of the interplanetary field departed considerably from the average archimedean spiral direction, causing the azimuthal component of the field to be in the opposite direction to that expected for a spirallike field. This led *Friis-Christensen et al.* [1972] to suggest that the cause of the effects observed in the polar geomagnetic field was not the IMF polarity as such but rather the direction of the azimuthal component of IMF. It is, however, relatively rare that the IMF deviates so much from the spiral direction that the sign of the IMF polarity and the sign of its azimuthal component differ.

In this paper we shall examine the magnetic disturbance patterns in the polar cap observed on days with the same IMF polarity. We will show that a circulating ionospheric Hall current flowing at about 82° invariant latitude eastward around the northern magnetic pole explains the observed perturbation when the earth is within an away sector. When the earth is immersed in a toward sector, a westward current of about the same strength and location fits the observations.

Since it is possible to infer the IMF polarity on almost every day, we are led to the following explanation of the observed high-latitude geomagnetic disturbances: During the day hours a system of ionospheric Hall currents encircles the magnetic poles on every day. The current system may extend up to 15° from the pole, being strongest at 8°–10° invariant colatitude. The current direction as seen from the earth is counterclockwise in away sectors and clockwise in toward sectors. Finally, the current strength is dependent on season, being strong during local summer and weak during the winter.

The existence of a current system inside the polar cap encircling the magnetic pole during local day hours calls for a major revision of the currently accepted picture of polar cap geomagnetic variations. It also suggests a new framework for interpreting polar cap observations of geomagnetic and related phenomena.

DATA ANALYSIS

The present study uses geomagnetic data supplied by World Data Center A for Geomagnetism, as well as sector polarity data given by *Wilcox* [1968]. The analysis extends over the year 1965, partly due to availability of digitized data for that interval. To eliminate days on which the IMF was not close to the spiral direction or when the field was of mixed polarity, the following procedure was used: Using Z magnetograms from Resolute Bay and from Thule, the IMF polarity was inferred independently for each day of 1965 whenever possible. For details about the method, see *Svalgaard* [1972]. Only days on which the IMF polarity inferred from both stations and the polarity measured by spacecraft all agreed were then selected. Table 1 shows the measured IMF polarities, together with the inferred polarities.

The sector structure itself is somewhat of an abstraction, and there are some days where the IMF does not have a clearly defined preferred direction. Furthermore, temporal evolution or changes in the polar cap current system may cause disagreements between the polarities inferred from different stations. But in spite of these factors the polarities inferred from Thule and from Resolute Bay agree on 199 days out of 233, or 85%.

Hourly mean values of the geomagnetic field components for nine stations in the northern hemisphere were used in the analysis. This included four stations in the central polar cap, Alert, Thule, Resolute Bay, and Mould Bay; three auroral zone stations, Point Barrow, Fort Churchill, and Leirvogur; and two stations at intermediate latitudes, Godhavn and Baker Lake, which provided additional coverage. The geomagnetic field data were first converted to X, Y, and Z components and then corrected for secular variation. All days with data gaps were then excluded to allow meaningful daily variations to be computed.

Daily variations of all three components were then computed for each IMF polarity separately for the whole year, as well as for different seasons, a season being defined here as 120 days centered on a solstice or an equinox. Finally, the average daily variations through the year were computed using all days irrespective of IMF polarity. Since the computed daily variations consist of sets of 24 hourly field values instead of deviations from the daily mean value, they may be directly compared with each other. The uniformity of the average daily variation of the polar cap field as discussed in the introduction indicates that variations with period of several hours are not influenced very much by local inhomogeneities in subsoil conductivity. This is especially encouraging in the case of Alert, which shows severe induction effects for short-period variations.

Figure 2 shows the diurnal variation of the Z component at Resolute Bay; the open circles display the variation found on days where the earth is within away sectors, while the filled circles show the variation during toward sectors. For about half of the day the sector polarity does not seem to have any influence on the value of the Z component. However, during the other half of the day, roughly between 1200 and 2400 UT, the variation of the Z component is strongly dependent on the IMF polarity. On days with positive IMF polarity (away from the sun) the Z com-

TABLE 1. Measured IMF Polarity and the Polarity Inferred from Polar Cap Observations from Resolute Bay (RB) and Thule (TH) for 1965

		Day																										
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Jan. 1	IMF	−	+	+	+	+	+	+	−	−	−	−	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
	RB	−	−	−	+	+	+	−	−		+	+		+	−	+	+	−	+	+	+	+	−	−		+	+	+
	TH	−	+	+	+	−	+	−	−	−	+	−	−	+	+	+	+	+	+	+	+	+	−	+	+	+	+	+
Jan. 28	IMF	+	+	+	+	+	−	−	−	−	−	−			+	+	+	+	+	+		−		+	+	+	+	+
	RB	+	+	+	+	+	−	−	−	−	−	−	+		+	+	+	+	−	−	−	−	−	−	+	+	+	+
	TH	+	−	+	+			−	−	−	−	−		−		+	+	+	+	−	+	+	−	−	+	+	+	+
Feb. 24	IMF	+	+	+	+	+	+	+		+	+			+	+	+	+	+	+	+	+	+	+	+				
	RB	+	+	+		+		−	−	+		−	−	+	+	+	+		+			+	+	+	+	+	+	
	TH	+	−	+	−	+	−	−	−	+	+		+	+	+	−			+		+	+	+		+	+	+	+
March 23	IMF			+	+	+		+	+	+	−		+	+	+	+	+	+				−	−			+	+	−
	RB	+		+		+	+		+	+	+	+	+		+	+	−	+	+	+	−	−	+	+	−	+	−	+
	TH	+	+			+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+		+	+		+	−	+
April 19	IMF	+	+	+	+	+	+	+	+	+	+	+	−	−	+	+	+		−	−	−	−	−	−			+	+
	RB	+	+	+	+	+	+	+	+	−	+	−	+	+	+	+	+	−		−	−		−	−	+	+		
	TH	+		+		+	+	+	+		+		+	+	+	+	+	−	−	−	−	−	−	−	+		−	+
May 16	IMF						−	−	+		+	+	+	+	+	+	+	+	+	−	−	−	−	−	−	−	+	+
	RB	+	+	+	+	+	−	−			−	−	+	+	+	+	+	−	−	−	−	+	−	−	−	−	+	+
	TH	+	+	+	+	+	−	−	+		+	−	+	+	+	+		−	−	−	−	+	−	−	−	−	+	+
June 12	IMF	+	+	+	+		+		−	−	−	−	−	−		+		−	−	−	−	−	−	−	−		+	+
	RB	+			−	−	+	+				−	−	−	+		+			−	−	−			−	+	+	−
	TH	+	+	−	−		+	+	−	+	+		−	−	+	+	+			−	−		−	−	−	+	+	−
July 9	IMF		−	−		−			−	−	−	−			−	+	+	+			−	−	−	−			−	
	RB	−		−	+	−	−		−	+	+	−	−	+		+	+	+	+	−	−	−	−	−	−	−	−	+
	TH		+	+		−	−	+		+	+		−	−	−	+	+	+	+	−	−	+	−	−	−		−	+
Aug. 5	IMF				−	−	−	−	−	−	−	−	−	−	−		+	+	+		−	−	−	−	−	−	−	−
	RB	−		−	−	−	+	−	−	−		−		−	−	+	+	+	+	−		−	−	−	−			−
	TH	+	+	−	−	−	+	−	−	−			−	−	−	+		+	+		−	−	−		−		−	−
Sept. 1	IMF	−	−	−			−	−	−	−		−	−	−	−	−		+	+	+	+	+		−	−	−	−	
	RB	−	−	+	−	−		−	−	−	+	−		+	−	−	+	+	+	+	+	+	−	−		−	−	+
	TH	−	−		−	−		−	−	−	+	−			+	−	+	+	+	+			−	−	−	−	−	+
Sept. 28	IMF			−	−	−	−		−	−	−	−	−		−	−	−	−	−		+	+	+	+	−	−		+
	RB	−	−	−		−	−		−	−	−	−	−			+	+	−	−	+	+	+	+	+	+	−	+	+
	TH		−	−			−	−	−	−	−	−	−		+	+	+	+	−			+	+	+	−	−	+	+
Oct. 25	IMF	+	−	−	−	−	−	−	−	−	−	−		+	+			−	−	−				−	−		+	+
	RB	+	−	−	−	−	−	−	−	+	−	+	−	+	+	+	−	−	−	+	+	−	−	−	−	+	+	+
	TH	+	+	−	−	−	−	−	−	+	−	−	−	+	+	+	−	−	−	−	−	−	+	−	+	+	+	+
Nov. 21	IMF	+	+	+	−	−		−	−	−		+					−	−	−	−	−	−	−		−	−		
	RB	+	+	+	−	−	−	−	−	+	−	−	−	+	−	+	+	−	−	−	−	−	−	+	−	−	+	+
	TH					−	−	−	−	+					−	−		−	−		−		−	+	+	−	+	+
Dec. 18	IMF	+	+	+	+	−	−	−			+	+	+	+	+													
	RB	−	+	+	+	−	−	+		+	+	−	−	+	+													
	TH		+	−	+	−	−	+		−	−			+	+													

The data are ordered in 27-day periods. A plus sign is the signature for a day with positive (away) polarity, a minus sign is the signature for a day with negative (toward) polarity, while a blank indicates a day where the polarity is unknown or badly defined. The days are divided into groups of seven. Note that on several days the polarities inferred using both RB and TH mutually agree but disagree with the IMF polarity measured by spacecraft. All such days were excluded from the analysis.

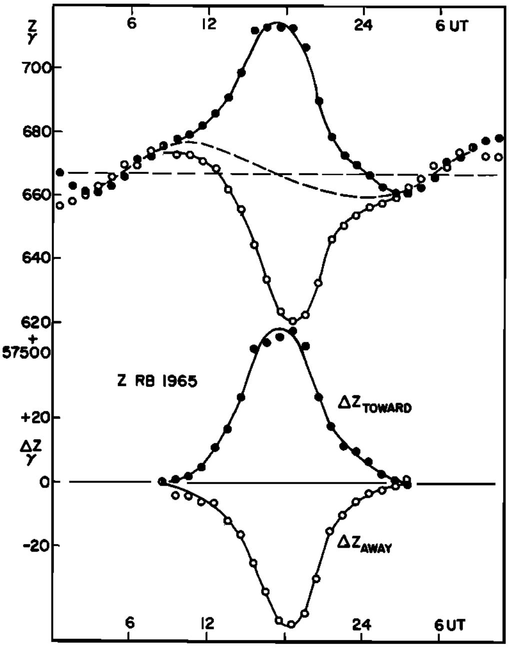

Fig. 2. Daily variation of the vertical component at Resolute Bay for 1965. Open circles show the variation on days when the earth was immersed in interplanetary sectors of the magnetic field pointing away from the sun. Solid circles show the variation during toward sectors. The dashed curve is the average variation on all days irrespective of the sector polarity, and the straight dashed line indicates the location of the quiet undisturbed level. The average variation has been subtracted from the data in the lower panel of the figure.

ponent is decreased and reaches a minimum around 1800 UT, while on days with negative polarity the Z component is increased by about the same amount for about the same interval of time as the decrease on days having positive polarity.

The average daily variation found for all days of the year is shown by the dashed curve in Figure 2, demonstrating the almost complete cancellation of the sector polarity influences when about the same number of days with opposite IMF polarity is averaged together. This result suggests that the same mechanism is responsible for both the increase of the Z component during toward sectors and for the decrease during away sectors, the sign of the change in the Z component being determined only by the sector polarity or more strictly by the sign of the azimuthal component of the interplanetary magnetic field. When the average daily variation is subtracted from the data, only the sector polarity influence on the Z component remains, and this is shown in the lower part of Figure 2.

We have discussed this figure at some length because the influence of IMF polarity on the vertical component at Resolute Bay is rather typical for other polar cap stations and for other magnetic elements as well. For any given polarity of the IMF we find a certain deviation (taking place roughly between 1200 and 2400 UT) from the simple all-year average daily variation of each magnetic element. For the opposite polarity, about the same deviation is observed but with the opposite sign. Figure 3 shows another example of this general behavior for the north component at Resolute Bay. In this figure the dashed curve showing the average diurnal variation (for all days irrespective of the IMF polarity) has been slightly smoothed to approximate the simple sinusoidal variation.

The same smoothing procedure has been applied to all average daily variation data used

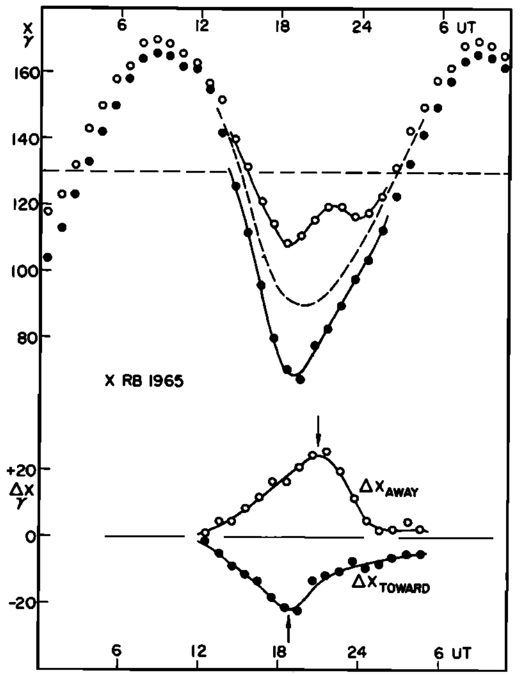

Fig. 3. Daily variation of the north component at Resolute Bay for 1965. The format is the same as that used in Figure 2.

in this study. The effects of the smoothing are in all cases rather minor, never exceeding 5 gammas. Since this is but a small fraction of the total variations, no significant bias is introduced by the smoothing.

The daily variations for the two IMF polarities taken separately are based on about 80 days of each polarity, whereas the yearly average daily variations shown by the dashed curves are based on most of the days through the year (usually about 350 days excluding those with data gaps).

In 1965, severe worldwide magnetic disturbances occurred on only 2 days (April 18 and June 16), and both these days were excluded from the analysis because they did not fulfill the criterion that the IMF polarity measured by spacecraft and inferred from Thule Z and from Resolute Bay Z must all agree. As a whole, 1965 was a very quiet year, so that the results are probably not biased by excessive geomagnetic activity.

The results of the present analysis rest on the assumption that the regular nearly sinusoidal diurnal variation of the magnetic elements described in the introduction and approximately given by the slightly smoothed all-year average variation is a real phenomenon, probably caused by activity outside the central polar caps. The influence of the sector polarity is then thought to be superposed on the simple diurnal variation and may be extracted by subtracting this variation from the observed diurnal variation of a given element for a given polarity. Examples of the result of the subtraction are given in the lower part of Figures 2 and 3. The assumption of superposition of the simple diurnal variation and the IMF polarity effects may be justified by examining magnetograms for individual days when the polarity effects are of unusually short duration; in these cases the simple diurnal variation can be followed up to the onset of the polarity effects, and it continues with the same trend after the effects have ended.

POLAR CAP GEOMAGNETIC RESPONSE TO IMF POLARITY

By using the data and procedures discussed in the previous section, the nature of the influence of the polarity of IMF on the high-latitude geomagnetic field has been studied in detail. The polarity effects over the northern polar cap were found to be strongest at 1700–1800 UT. At that time it is local noon at the northern magnetic pole, and conditions are the most favorable for direct interactions between the solar wind and the polar cap geomagnetic field. At stations in intermediate latitudes (about 75°) the polarity effects are still clearly discernible, whereas there is only very slight indication of any IMF polarity influence at auroral latitudes (below 70°). The effects are thus well confined to the interior of the polar cap and cannot be interpreted as extensions of certain types of auroral latitude activity.

A synoptic presentation of the superposed disturbances observed at 1800 UT during away and toward IMF polarity sectors is given in Figures 4 and 5, respectively. Horizontal perturbations are shown as vectors attached to station circles for six stations in the northern polar cap. The simultaneous vertical perturbation is given as a signed number next to the station circle. The positions of the geographical pole (GP) as well as of the magnetic pole (MP) are indicated on the figures.

A word should be said about the definition of the sign of the vertical component. Traditionally, the Z component is considered positive when directed downward, i.e., toward the earth. Hence Z is positive in the northern hemisphere and negative in the southern hemisphere. A perturbation directed away from the earth is then negative in the northern polar cap and positive in the southern polar cap.

Analysis of Figures 4 and 5 reveals a clear systematic difference in the way the geomagnetic field is disturbed during conditions with opposite IMF polarities. For away IMF polarity (Figure 4) the horizontal perturbation vectors all converge toward the magnetic pole, and vertical perturbations directed away from the earth (negative in northern hemisphere) are observed near the pole while vertical perturbations toward the earth (positive in northern hemisphere) are seen below 80° invariant latitude. For toward polarity (Figure 5) the direction of all perturbations is reversed; horizontal perturbations diverge from the magnetic pole, and vertical perturbations toward the earth occur near the pole.

These magnetic effects are precisely what might be produced by a circulating ionospheric current flowing eastward around the magnetic pole during away sectors and flowing westward during toward sectors. The direction of the current around the southern pole is opposite to that of the northern, since the perturbation of the Z component has opposite signs in the two hemispheres [*Svalgaard,* 1972]. For an observer near a magnetic pole the current direction would be clockwise for toward IMF polarity and counterclockwise for away polarity in both hemispheres. The magnitude of the effect, however, seems to be largely independent of the polarity of the interplanetary magnetic field. There are indications [*Friis-Christensen et al.,* 1972] that the magnitude of the effect is proportional to the magnitude of the azimuthal component of the IMF, with the constant of proportionality depending on season, being largest during local summer.

From an analysis of geomagnetic data from seven stations in the northern and eleven stations in the southern hemisphere, *Mansurov and Mansurova* [1971*a*] deduced essentially the same current systems to account for the polarity effects observed within the polar caps. The present study fully confirms their results, which apparently have attracted little attention. Studying the polarity effects on single days, *Friis-Christensen* [1971] also concludes that the magnetic perturbations may be due to a current vortex with focus near Thule at about 1700 UT.

The magnetic effects of the zonal current systems described above have the same sign throughout the day for given stations and IMF polarity. This means that daily mean values of a given element should show systematic differences between days within IMF sectors with different polarity. Furthermore, by taking the mean value over a day, field variations of the simple sinusoidal type cancel out to enhance the superposed polarity effects. This allows us to make a simple straightforward analysis of the influence of different IMF polarities on the geomagnetic field.

The average values of the three components (X, Y, Z) were computed for all nine stations for three samples of the data through 1965; namely, (1) for all days within away sectors, (2) for all days within toward sectors, and (3) for all days irrespective of the sector polarity. Subtracting the average field values for the last sample from those of the first samples should then show any effects related to IMF polarity. Figure 6 shows the result plotted against invariant latitude. The IMF polarity effect in the Z component is again character-

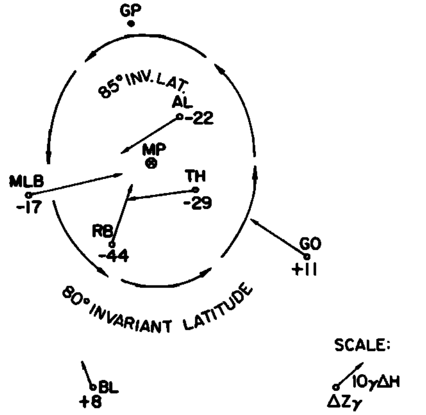

Fig. 4. Synoptic map of polar cap magnetic perturbations at 1800 UT during IMF away polarity. Horizontal perturbations are shown as vectors attached to the station circles for Alert (AL), Thule (TH), Resolute Bay (RB), Mould Bay (MLB), Godhavn (GO), and Baker Lake (BL). Vertical perturbations are given as signed numbers next to the station circles. A circulating ionospheric Hall current flowing eastward around the invariant magnetic pole (MP) is indicated in the figure. This current fits the observations and may produce the magnetic perturbations. The position of the geographical pole (GP) is also shown.

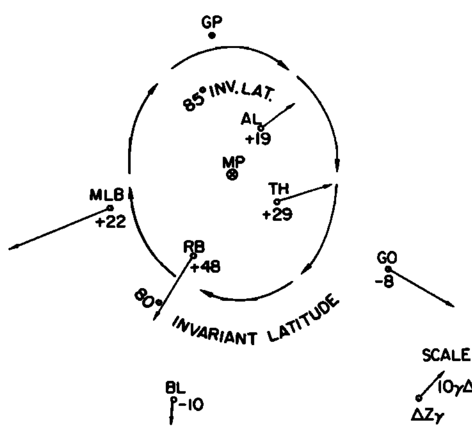

Fig. 5. Same as Figure 4 but for IMF toward polarity. The direction of all perturbations is reversed compared to the situation found for away sectors, and the current encircling the pole is also reversed.

istic of a current encircling the magnetic pole; the current direction again reverses when the IMF polarity reverses. The Z perturbation changes sign at about 80° invariant latitude suggesting that the current is most concentrated near this latitude. The magnitude of perturbations of the horizontal component across the polar cap is shown in the lower part of Figure 6. The horizontal effects are strongest at about 82° invariant latitude.

It is comforting that a simple and straightforward analysis using mean values over many days leads to the same conclusion as the analysis based on the somewhat more subtle diurnal variation of the magnetic elements, namely, that the IMF polarity effect on the geomagnetic field can be described as the magnetic effects of a current system encircling the magnetic poles at very high latitudes only. The current direction changes when the polarity of the interplanetary magnetic field changes.

Temporal Changes in the Polar Cap Current

If the nearly zonal polar cap current system around the magnetic poles is stationary in position, the direction of the magnetic perturbation vectors caused by it should not change during the day. The immediate impression from the analysis of the daily variation of the perturbations is that their direction indeed stays relatively constant throughout the interval in which they are observed. To examine this more quantitatively, the horizontal perturbation vectors for Thule, Resolute Bay, and Mould Bay are presented in Figure 7. It is evident from the figure that the direction changes observed during the 12-hour interval in question (1200–2400 UT) are in fact rather

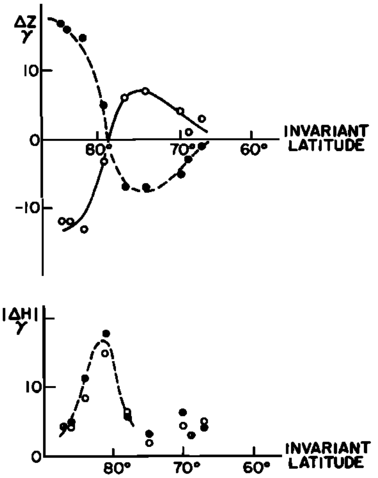

Fig. 6. The difference between the yearly mean of Z and H for both IMF polarities and the all-day average values is shown. The differences are plotted against invariant latitude for nine stations at high northern latitudes. Open circles are used for away polarity and solid circles for toward polarity.

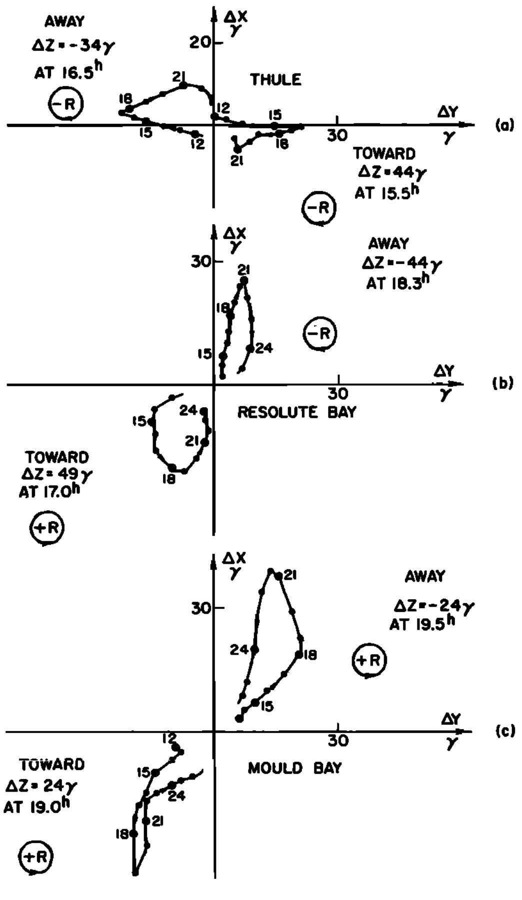

Fig. 7. Daily rotation of horizontal perturbation vectors for (*a*) Thule, (*b*) Resolute Bay, and (*c*) Mould Bay. Successive end points of the vectors are marked by the corresponding UT values at 3-hour intervals. The vectors tend to stay within the same quadrant for each IMF polarity. The time and amplitude for maximum vertical perturbation ΔZ are shown for each polarity for the three stations, as is the sense of rotation of the horizontal perturbation vectors. A $-R$ means clockwise rotation and a $+R$ means counterclockwise vector rotation, as viewed from above the pole.

small; the curve described by the end point of the vector is generally elongated either toward the magnetic pole or away from it. This indicates that the current system does not move very much during the day. On the other hand, the data are suggestive of a slight displacement toward the geographical pole of the current during the interval in which the effects of the current are observed.

The perturbation vector rotates clockwise at Thule and counterclockwise at Mould Bay, irrespective of the sense of the current (or of the IMF polarity), whereas Resolute Bay shows a transitional behavior in the sense that the vector rotates clockwise during away sectors and counterclockwise during toward sectors. Since Mould Bay is located roughly to the west of the magnetic pole, Thule is located to the east of the magnetic pole, and Resolute Bay is to the south, a slight south to north movement of the current system during the day accounts for the vector rotations observed. The data from Resolute Bay are the most sensitive to variations of the direction of movement but with no vector rotation on the average. By noting that the azimuthal change in the perturbation vectors is from 30° to 50° for stations 4°–8° from the pole, we can estimate the total displacement of the current system focus to be about 3° of latitude or 300 km, crossing the magnetic pole from south to north. Compared to the 15°–20° diameter of the current system, this displacement is but a minor secondary effect. The main conclusion is that the current system occupies the central polar cap around the magnetic pole throughout its existence.

While the location of the current system does not change very much, the magnitude of its magnetic effects (and therefore probably the current intensity) on the contrary shows a very marked variation throughout the day. This is easily seen in Figures 2, 3, and 7, where the largest perturbations are observed in the interval 1500–2100 UT, while the amplitude has decreased to 0 in the interval 0300–0900 UT. Table 2 gives the time of maximum perturbation of the vertical component for four stations in the northern polar cap. As the variation of the Z component is the integrated effects of a large section of the current system, this component is particularly well suited to show large-scale variations of the current intensity. The average time of maximum perturbation is about 1700 UT. This is close to the time of local noon over the northern magnetic pole.

TABLE 2. Maximum Perturbation of the Vertical Component for IMF Polarity in Universal Time

Station	Toward, hours	Away, hours	Local Noon,* hours
Alert	14.5	16.0	16.2
Thule	15.5	16.5	16.6
Resolute Bay	17.5	18.3	18.3
Mould Bay	19.0	19.5	20.0

* The time of local noon is given for comparison.

Despite the fact that there exists a local magnetic time difference of nearly 15 hours between Alert and Mould Bay, the time differences between maximum perturbation at different stations are much smaller and seem to correspond to the local time differences. It seems fair to conclude that the largest perturbations due to the polar cap current system are observed near local noon at all four stations.

The following interpretation of the data might be suggested. When the magnetic pole is on the nightside of the earth, the polar cap current is absent or very weak. When the rotation of the earth brings the magnetic pole into the dayside, the polar cap current system develops, the current being most concentrated in the part of the current system that is nearest the noon meridian. The current increases its total intensity until the magnetic pole is rotated past the noon meridian; then the intensity starts to decrease as the magnetic pole approaches the nightside again. The initial development of the current system seems to be strongest slightly south of the magnetic pole; the current density is then increasing northward during the day hours.

There is an interesting asymmetry between the two IMF polarities with regard to the time of maximum development of the northern polar cap current system. The current seems to reach its maximum intensity about 1 hour earlier during toward IMF polarity than during away polarity. This effect is clearly seen in Table 2 as well as in Figure 7. It is not known if the same asymmetry is present in the southern polar cap or if it goes in the opposite direction. The fact that the polar cap current develops on the dayside and also the finding of *Friis-Christensen et al.* [1972] that the azimuthal component of IMF is the critical component in determining the sense of the polar cap current indicate that the mechanism responsible for the current works most effectively in the front of the magnetosphere near the cusp region. A slight displacement of the cusp region in the direction of the azimuthal component of IMF could be the cause of the asymmetry in the maximum development of the polar cap current for different IMF polarities. There are indications [*Friis-Christensen,* 1971] that the asymmetry may be as large as 3 hours during sunspot maximum years, whereas the 1-hour difference found in the present study refers to sunspot minimum.

SEASONAL VARIATIONS OF THE POLAR CAP CURRENT

The magnitude of the influence of the IMF polarity on the polar geomagnetic field exhibits a very clear seasonal variation, being largest during local summer. Since the effects are almost equal in magnitude but with opposite sign for opposite IMF polarities and since the effects last about half a day, a simple measure of the magnitude of the polar cap perturbations for a given season would be the difference between the seasonal average of the Z component during toward sectors and the average for away sectors for the same season. By taking the difference ΔZ, we double the effect, but by taking averages over whole days instead of the interval where the effects are seen, we halve the doubled magnitude again. The seasonal variation of ΔZ for three polar cap stations is shown in Figure 8. The magnitude of the effect

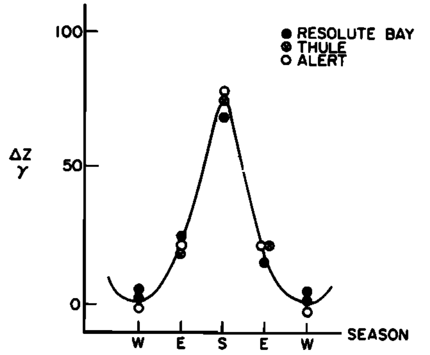

Fig. 8. Seasonal variation of the magnitude of the vertical perturbations caused by the polar cap current.

is very small during winter but increases sharply toward the summer. In addition, we note that the change throughout the year is nearly identical for all three stations; this seems to be a consequence of the fact that all three are well within the rather uniform perturbation field of the encircling polar cap current.

The very pronounced seasonal variation of the intensity of the polar cap current may be an indication of dependency on ionospheric conductivity or on the tilt of the magnetic axis of the earth, or on both.

There exists another seasonal effect in the time of maximum perturbation, which for the northern polar cap stations studied occurs earlier during the summer than during the winter. Table 3 lists the time of maximum perturbation for five stations during different seasons. In this table, no distinction has been made between the two IMF polarities, because the time difference between maximum perturbation for the two polarities taken separately is small and constant. There is a progressive change

TABLE 3. Seasonal Variation of Time of Maximum Perturbation of Polar Cap Geomagnetic Field

Station	Winter, hours UT	Equinox, hours UT	Summer, hours UT	Change, hours	Latitude, deg
Alert	18.0	14.0	13.0	5.0	82.5
Thule	18.0	15.5	15.0	3.0	77.5
Mould Bay	21.5	19.5	19.0	2.5	76.2
Resolute Bay	18.5	18.0	17.5	1.0	74.7
Godhavn	17.0	16.5	16.5	0.5	69.2

Average time for both polarities of IMF is given because there is no systematic difference between the two polarities with regard to the change to earlier hours of the perturbations during summer. The total change from winter to summer is also given together with the geographic latitudes of the stations.

toward earlier hours of maximum perturbation as we go from winter to summer. This effect might depend on geographical latitude; it is largest at the northernmost station, Alert, and becomes smaller with decreasing geographic latitude. There is evidence (Figure 9) from Vostok (invariant latitude −84.9°) that this seasonal effect is reversed in the southern polar cap, so that the time of maximum perturbation changes toward later hours from winter toward local summer. However, more study of this particular effect is needed before a definitive conclusion can be reached on that point.

We have shown that significant daily and seasonal variations of the location and intensity of the polar cap current system exist; their nature suggests that ionospheric conductivity as well as magnetospheric geometry probably both play a role in the mechanism responsible for originating and maintaining the polar cap current system. The variation of ionospheric conductivity across the polar cap is so small that the small-scale variations of the morphology of the current system (such as an earlier development of the system during toward sectors) cannot be explained by differences in conductivity.

SEASONAL VARIATION OF MAGNETIC ELEMENTS IN THE POLAR CAP

It has been suggested by *Nishida et al.* [1966] that the varying shape of the magnetosphere during the year, due to the varying angle between the average solar wind velocity and the geomagnetic dipole axis, should result in a seasonal variation in the vertical component of the polar magnetic field. Although a simple application of the mechanism proposed by Nishida et al. would predict much larger variations in the horizontal component (of the order $\Delta H \cong Z\Delta Z/H$) than in the vertical component, as to render their explanation dubious, it has been shown by a number of authors [*Mansurov and Mansurova*, 1971*b*, and references therein] that systematic seasonal variations of (for instance) monthly mean values of the magnetic elements do exist indeed even at high latitudes. In summary, the magnitude of the vertical component is decreased during local summer, and the horizontal component directed toward the geographical pole is increased. This effect

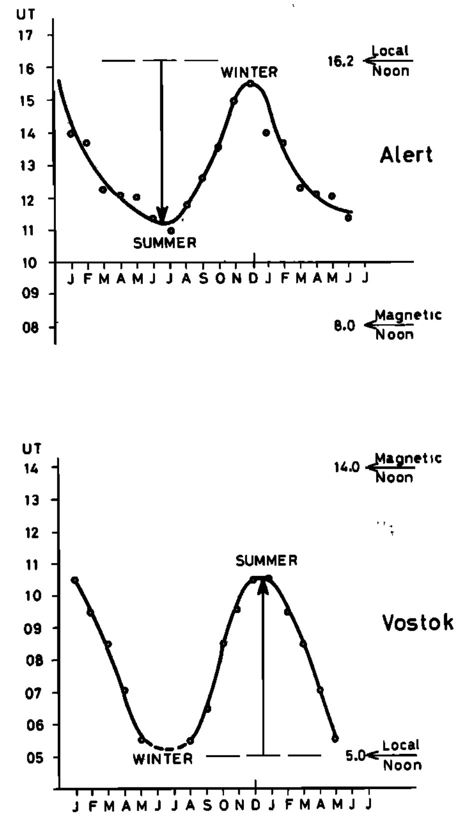

Fig. 9. Monthly mean time (modal value) of the maximal Z perturbation on days with inferred toward IMF polarity for Alert in the northern polar cap during 1964 and on days with inferred away polarity for Vostok in the southern polar cap for 1959–1961.

was confirmed from the data used in the present analysis, and the results are illustrated in Figure 10. The cause of this variation is unknown, but it is probably of magnetospheric origin, related in some way to the varying geometry of the interaction between the solar wind and the geomagnetic field.

The magnetic effects of the polar cap current system discussed in this paper introduce an important modulation of the seasonal variation of the magnetic elements. If there is a greater number of days with one polarity than with the other during any given season, then the mean value of the field components for that season would be contaminated by the IMF polarity effects. *Mansurov and Mansurova* [1971*b*] have commented on this problem and explained why the seasonal variation of the

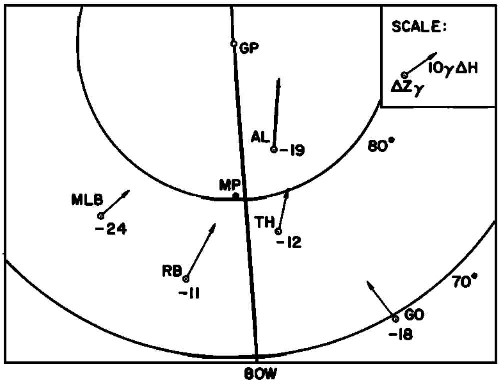

Fig. 10. Synoptic map of systematic differences between summer and winter mean values of the magnetic elements for the northern polar cap during 1965. Average horizontal difference is 14 γ pointing northward, and the average vertical difference is 17 γ pointing upward.

field in some years is simple and regular, while in other years it is irregular and distorted. This is simply the effect of variations in the proportion of one IMF polarity to the other. A regular variation of this kind has been suggested by *Rosenberg and Coleman* [1969], namely, that the predominant polarity of the IMF observed near the earth has an annual variation that changes sign when the heliographic latitude of the earth changes sign. Using the 45 years of interplanetary field polarity inferred by *Svalgaard* [1972], *Wilcox and Scherrer* [1972] were able to give a quantitative confirmation of this annual variation. There are also indications of a complex sunspot cycle variation of the predominant IMF polarity (see the review by *Wilcox* [1972]). We should therefore expect corresponding modulations of the seasonal variation of the polar geomagnetic field.

Figure 11 presents a summary of the seasonal variations of the three field components as observed during 1965 for several northern polar stations for both IMF polarities separately as well as the average variation irrespective of sector polarity. In this figure, as in Figure 2, open circles show the variation during IMF away polarity, solid circles the variation during toward polarity, and dashed curves the average variation. One may note in particular that the seasonal variation of the Z component comes out very small during toward polarity, while it is enhanced during away polarity. Interpreting the seasonal variation of the geomagnetic elements shown by the dashed curves as the combined result of a basic rather uniform variation and of persistent magnetic perturbations being largest during the summer season, as shown in Figures 12 and 13 separately for both IMF polarities, provides a satisfactory explanation of the observed and sometimes complex variations summarized in Figure 11.

In preparing Figure 11, no days have been excluded on the basis that the inferred IMF polarity disagreed with that observed in space. In this way, more data could go into the figure, and at the same time we get a check on whether any artifacts have been introduced by the exclusion. The main effect of using all data is a somewhat reduced amplitude of the magnetic perturbations, which one would expect due to spurious deviations from the ideal spiral direction of the IMF; but apart from this, no significant influence on the results could be detected.

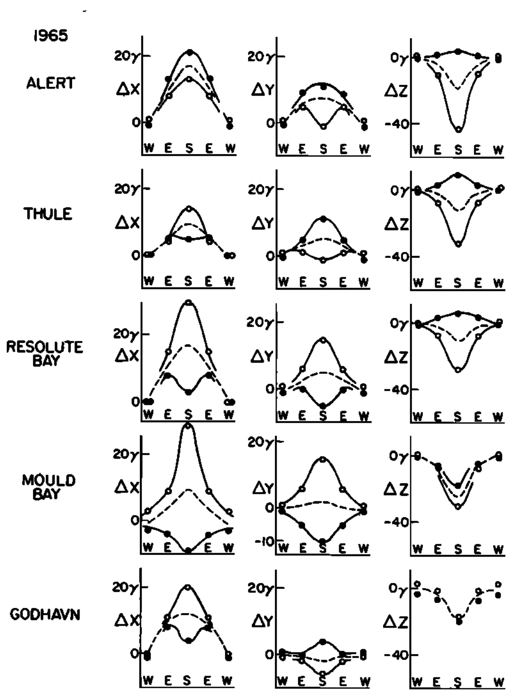

Fig. 11. Seasonal variation of the magnetic elements in the northern polar cap during 1965 shown separately for IMF away polarity (open circles), toward polarity (solid circles), and for all days in each season (dashed curves). The W, E, and S mean winter, equinoctial, and summer season, respectively.

The perturbations shown in Figures 12 and 13 correspond closely to what we would expect from the polar cap current system, thus confirming the importance of that system in understanding polar magnetic variations.

DISCUSSION

The rather specific interaction between the interplanetary magnetic field and the polar geomagnetic field discussed in the present paper could give important clues to improved physical understanding of the interaction processes between these two fields.

Wilhjelm and Friis-Christensen [1971] and *Jørgensen et al.* [1972] have suggested that an electric field, which is induced in the magnetosphere by merging of interplanetary and geomagnetic field lines, is transmitted to the ionosphere along equipotentials of the polar cusp field lines, the electric field vector being determined by the azimuthal component of IMF. This mechanism produces zonal currents along short segments of approximately equal invariant latitude but fails to explain the closed polar cap current system reported in the present study. The particular mechanism proposed by the above authors relies on the unreasonable assumption that the electric field is confined to the region where the merging is taking place. A more realistic treatment of the merging process might lead to a more satisfactory theory.

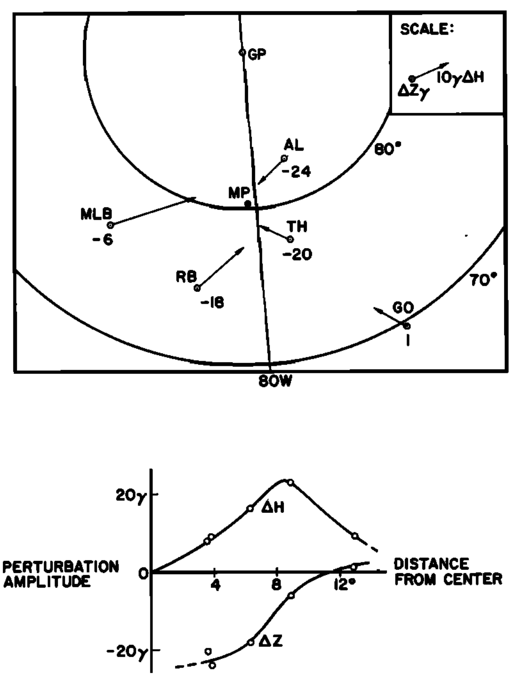

Fig. 12. Synoptic map of the difference between the mean values of the magnetic elements for days within IMF away sectors within 120 days centered on summer solstice and the all-day seasonal average for the summer of 1965 over the northern polar cap. The format is similar to that in Figures 4 and 5. The amplitude of the perturbations as a function of invariant latitude is shown in the lower panel. Compare with Figure 6.

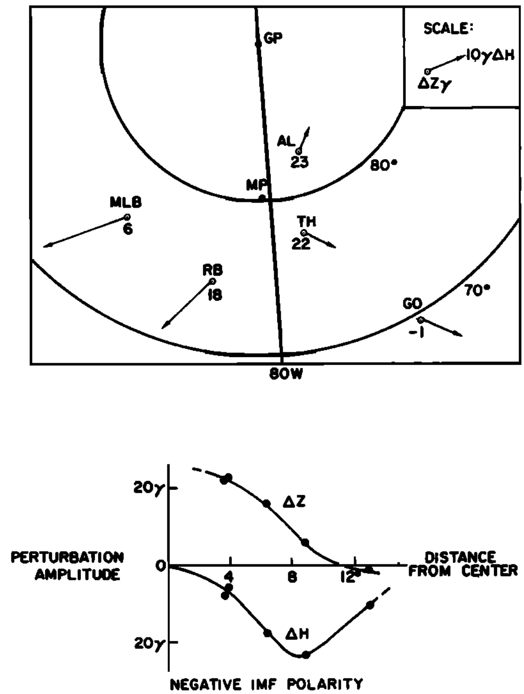

Fig. 13. Same as Figure 12 but for days within toward sectors.

Bassolo et al. [1972] have sought an explanation for the sector polarity effects in a mechanism involving interaction between the radial component of the IMF and the geomagnetospheric tail field. But since the azimuthal IMF component seems to be the effective one, the mechanism proposed by Bassolo et al. is probably not applicable.

Heppner [1972*a*, *b*] has discovered a dawn-dusk asymmetry related to the IMF polarity in the polar cap electric fields observed by satellite. When the earth is within an IMF away polarity sector, a maximum polar cap electric field is observed on the evening side at southern high latitudes. When the earth is within a toward sector, the situation is reversed. However, the shifts of the polar cap–auroral belt boundary proposed by *Heppner* [1972*b*] to explain the observed influence of the IMF polarity on the polar cap magnetic field do not reproduce the more detailed pattern of magnetic perturbations reported in the present paper. There is, however, little doubt that electric field measurements may provide important clues toward the understanding of the polar cap phenomena.

Stern [1972] has discussed the possibility that unipolar induction between the magnetosphere and the moving magnetosheath may feed energy from the solar wind into the magnetosphere and high-latitude ionosphere, explaining the correlation of the azimuthal component of IMF with polar electric fields and with polar magnetic variations. Stern considers unipolar induction in a circuit configuration, where a current from the magnetosheath enters the polar cusps along the field lines, then flows across the polar cap in the ionosphere, and from the nightside of the polar cap completes the circuit along tail field lines and the plasma sheet to the magnetosheath. For the opposite IMF polarity the current flow is reversed. It has been pointed out (D. P. Stern, personal communication, 1972) that this theory encounters some serious problems. In particular, if the IMF parts smoothly to allow the magnetosphere to pass through it, the two polar cusps will intersect two neighboring interplanetary field lines and will be effectively short-circuited to each other; in addition, no external flux is cut by the magnetosphere in this case, so that no unipolar effect arises from its motion relative to the solar wind.

Kawasaki and Akasofu [1972] propose that the so-called *DP* 2 variations [*Nishida and Kokubun*, 1971] and the variations described in the present paper are related and that a single current system or mechanism is responsible for both types of variations. Furthermore, they tentatively conclude that all variations in the polar cap are associated with polar magnetic substorms. The present study does not support this view, and we are still left with the problem of a new and unexpected polar cap current system.

The present network of stations does not adequately cover the Siberian side of the polar cap, and this introduces some ambiguity as to the precise shape of the polar cap current system. The pattern proposed in the present paper is the simplest one not contradicting the observations. It is possible that future investigations will reveal a more complicated and sophisticated current system. At present, no satisfactory theory exists for the very direct and specific solar-terrestrial relationship connecting the polar cap geomagnetic field to the azimuthal component of the interplanetary field.

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