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Leif Svalgaard

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Abstract

The recently discovered relation between the azimuthal component of the interplanetary magnetic field and magnetic variations in the earth's polar caps is reviewed. When the IMF azimuthal component is positive (typical of an interplanetary sector with magnetic field directed away from the sun) geomagnetic perturbations directed away from the earth are observed within 8° from the corrected geomagnetic pole. When the IMF azimuthal component is negative (typically within toward sectors) the geomagnetic perturbations are directed towards the earth at both poles. These perturbations can also be described by an equivalent current flowing at a constant magnetic latitude of 80°-82° clockwise around the magnetic poles during toward sectors and counterclockwise during away sectors. This current fluctuates in magnitude and direction with the azimuthal component of the IMF, with a delay time of the order of 20 minutes. The importance of this effect for our understanding of both solar magnetism and magnetospheric physics is stressed in view of the possibility for investigating the solar sector structure during the last five sunspot cycles.

THE RELATION BETWEEN THE AZIMUTHAL COMPONENT OF THE INTERPLANETARY MAGNETIC FIELD AND THE GEOMAGNETIC FIELD IN THE POLAR CAPS

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Introduction

Of all solar wind parameters, it appears to be the interplanetary magnetic field (IMF) which is most directly related to terrestrial effects. Dungey (1961) suggested that a southward directed IMF may merge with the geomagnetic field and enhance the convection of magnetospheric plasma. In particular, Dungey suggested that the classical SD current system arose from such a mechanism. Many recent investigations have confirmed the existence of such a relationship (e.g., Meng et al., 1973). The influence of a southward IMF component has played an important role in many theoretical investigations of the interaction between the solar wind and the terrestrial magnetosphere, especially in attempts to understand the mechanism of polar substorms. For some other aspects of magnetospheric physics, it is, however, apparent that the southward component of the IMF does not play a major role. Access of solar particles to the polar caps seems to be unaffected by the north-south component (Fennell, 1973); and the spatial configuration of the polar cap electric field as observed by Heppner (1972) is controlled by the azimuthal (east-west) component of the IMF. Finally a distinct variation of the geomagnetic field in the polar caps has been found to depend critically upon the azimuthal component of the IMF (Svalgaard, 1968, 1972, 1973a; Mansurov, 1969; Friis-Christensen et al., 1971, 1972; Wilcox, 1972; Kawasaki et al., 1973).

The discovery of these particular variations has sparked considerable controversy and re-thinking about the nature of polar cap magnetic variations, and will be the subject of this review. Part of the controversy is due to the fact that the influence of the north-south component was predicted, while the influence of the azimuthal component was not. But, as has been pointed out by Vasyliunas, no quantitative models of the open magnetosphere exist at present, and therefore it is not clear what the detailed predictions of the open magnetosphere concept are. There is even some doubt as to exactly how necessary the southward component is in controlling geomagnetic activity now that it has done its job in resolving the open versus closed magnetosphere controversy.

Polar Cap Magnetic Field Variations

The diurnal variation of the geomagnetic field in the polar caps was 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 kind of observations leading to this picture. The average daily variations during the summer season of the North component, X, and of the East component, Y, at an observing station near the magnetic pole, are sinusoidal to within a few gammas, and their phases differ by six hours. The uniformity of the variation across the polar cap is also illustrated in the figure. Figure 1(b) shows that the time of maximum X is controlled by local time, i.e., the rotation of the earth. The amplitude of the regular diurnal variation is very nearly constant over the polar cap as shown in Figure 1(c), being larger during summer than in winter.

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 the observing station then is closer to the polar electrojets. For very high latitude stations this amplitude is in general much smaller than the amplitude of the variation in the horizontal components. This makes the Z component particularly well-suited for studies of variations unrelated to the polar electrojets.

We do not believe today that a horizontal sheet current actually flows across the polar cap. Electric field directions derived from Barium releases in the polar ionosphere show that the magnetic effects must be caused almost entirely by a source other than overhead ionospheric currents (Heppner et al., 1971). Whatever the detailed mechanism may be, it is generally believed that some of the currents which close the auroral electrojets are the cause of the uniform perturbation field across the polar cap, and therefore the cause of the regular daily variations. Possibly field-aligned current sheets flowing nearly vertically into and out of the ionosphere may be of importance in producing the variations as has been suggested by Heppner et al. (1971) and by Kawasaki and Akasofu (1973).

By means of the polar electrojet, 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. The special polar cap disturbances differ from auroral latitude activity in several ways, the most obvious being that auroral latitude activity peaks at midnight while polar cap disturbances are most prominent around noon. The polar cap disturbances were usually described as being irregular without distinct patterns; sometimes the perturbations were positive and sometimes negative, so that they tend to cancel out when several days are averaged; in this way the average daily variation takes on its simple form as shown in Figure 1. However Svalgaard (1968) and independently Mansurov (1969) were able to classify the polar disturbances into two clearly different types and showed that they were closely related to the direction of the interplanetary magnetic field.

The two different types are most clearly seen in the vertical, Z, component at stations close to the invariant poles, such as Thule in the northern hemisphere and Vostok in the south. Figure 2 shows typical variations at these two stations. One observes either a substantial increase of the vertical component for several hours around local noon, or on other days a decrease. A change from one type of variation (e.g., increases) to the other type occurs at the same time at both stations. Typically one type is observed to persist for several days, then the variation may change, often quite abruptly, to the other type, which then is observed for the following several days, etc.

Interplanetary Sector Structure

The interplanetary magnetic field is an extension of the weak solar photospheric magnetic field carried out by a steady expansion of the solar corona: the solar wind. The magnetic field lines are "frozen" into the plasma and move with it. Due to interactions between inhomogeneities in the plasma and the high speed ($\approx$ 400 km/sec) of the solar wind, this interplanetary magnetic field is highly variable on a short time scale (i.e., minutes) as observed near the earth. If the field components are averaged over a few hours, much of this variability disappears and a larger scale field-structure emerges (Wilcox, 1968). In general, the average field is either directed away from the sun along an Archimedean spiral line resulting from combining the radially outflowing solar wind with the rotation of the sun, or directed towards the sun along the spiral. Near the earth the spiral angle is about 45^o. The average field is usually in the same direction (i.e., either away from the sun or toward the sun) for several consecutive days. Then the avarage field direction changes abruptly to the opposite direction, which is then observed for the next several days. The interplanetary magnetic field can thus be divided into regions called sectors where the field direction is dominantly in the same direction either towards the sun or away from the sun along the spiral line. Usually there are four such sectors so that the earth is swept by IMF with the same predominant direction for about 27/4 ≈ 7 days. It is important to note that this sector-structure only emerges if the field components are averaged over sufficiently long intervals (e.g., three hours), and that on a shorter time scale the IMF is highly variable in both magnitude and direction.

Polar Cap Response to IMF Polarity

The IMF polarity and the type of polar cap variation have the common property of staying the same for several days and then abruptly changing to the opposite. By closer examination it is indeed found that these changes take place simultaneously, so that when the earth is within an away IMF sector the variation shown in Figure 2(a) is observed, while the other type shown in Figure 2(b) is seen when the earth is immersed in a toward-the-sun directed interplanetary field. We can summarize the description of this surprising effect and at the same time provide a useful mnemonic by saying that during an away sector the polar cap disturbance field is directed away from the earth at both poles. When the earth is within a toward sector, the disturbance field is directed toward the earth at both poles. The magnitude of this effect varies with season, since it is largest during local summer when a disturbance field of several hundred gammas is not uncommon. It is thus important to note that the influence of the IMF polarity on the polar cap magnetic variations is not a subtle, minor or hard-to-detect effect, but is usually dominating over all other processes disturbing the polar cap field.

Therefore it is normally a straightforward procedure to infer what the IMF polarity is just by inspection of a polar cap Z magnetogram. As an unambiguous test of the effect, the IMF sector polarity was inferred from the polar cap station Thule for the years 1969 and 1970. This was done by Friis-Christensen et al. (1971) for 1969 and by Svalgaard (1972) for 1970. In both cases it was done before the sector polarity observed by spacecraft was available. The sector polarity was deduced by visual inspection of the magnetograms, and no scaling or computing was performed. Figure 3 shows a comparison with the observed polarity for 1969. The correspondence between the inferred and the observed sector polarities is very close. The positions of the sector boundaries usually agree to within less of a day. The same close agreement was found for the 1970 comparison. Table 1 summarizes the number of days with agreement and the number of days with disagreement for the two years separately.

IMF polar cap	away	toward
away	71	11
toward	7	85

1969: 90% correct

IMF polar cap	away	toward
away	95	16
toward	25	105

1970: 83% correct

Table 1. Time (in days) for each combination of polarity of the interplanetary magnetic field observed with spacecraft (IMF) and inferred from observations of polar geomagnetic field (polar cap) for 1969 and 1970. Days with missing data or mixed polarity are excluded. After Friis-Christensen et al. (1971) and Wilcox and Colburn (1973).

The detailed agreement between the IMF sector polarity as observed by spacecraft near the earth and as inferred from polar cap magnetograms leaves no doubt about the reality of the close relationship between the two fields and is also a very good argument for an open magnetosphere versus a closed one.

Critical Component of IMF

Even if the agreement between the sector polarity measured by spacecraft and inferred from the ground is very close (≈ 85%) there are times where the polar cap magnetograms show the signature for a sector polarity opposite to the one observed by spacecraft. In a study of these disagreements, Friis-Christensen et al. (1972) noted that on some of these days the dominant direction of the interplanetary field departed considerably from the average Archimedean spiral direction, so that the azimuthal component of the field was in the opposite direction to that expected for a spiral field. This led to the suggestion that the cause of the effects observed in the polar cap was not the polarity of the interplanetary field as such, but rather the direction of the azimuthal (east-west) component of this field. Further investigations have confirmed that this is indeed the case. However, the interplanetary field direction is almost always near enough to the spiral direction that an azimuthal component in one direction corresponds to a given polarity of the IMF.

Friis-Christensen et al. (1972) plotted hourly mean values of the vertical component, Z, at Thule versus hourly mean values of the components of IMF. The coordinate system used by them was the geocentric solar magnetospheric system (GSM) in which the X axis points toward the sun from the center of the earth, the Y axis is perpendicular to the X axis and to the earth's magnetic dipole, so that the X-Z plane contains the dipole axis and the Z axis is positive in the northward direction. In this coordinate system the components of the IMF are BXM, BYM, and BZM. For the ideal spiral direction of IMF in an away sector BXM is negative and BYM is positive, whereas in a toward sector BXM is positive and BYM negative.

Friis-Christensen _et al._ found that if the IMF components were compared with the Thule Z component one hour later the best correlations were obtained. Figure 4 shows their result for the summer 1969. It is evident that the IMF component best correlated with Thule Z is BYM, while there seems to be little or no correlation with the two other IMF components.

That the relation between Thule Z and the IMF azimuthal component holds not only on a daily or hourly basis, but extends even to short-period fluctuations was demonstrated by _Kawasaki et al._ (1973). This is clearly seen in Figure 5 where the Thule Z-component is superposed on the IMF Y-component observed by the IMP-3 satellite. The records have been slightly shifted with respect to each other to obtain the best visually observable correlation for the short-period variations. The two records are remarkably well-correlated during the day hours (10 - 22 UT). Even variations of the IMF Y-component on a timescale of 20 minutes appear to be correlated with similar structures in the Thule Z records. On the average the variations of Thule Z are delayed about 25 minutes with respect to variations seen at IMP-3. This delay is considerably longer than the mean transit time (< 10 minutes) for the solar wind from the spacecraft to the earth, so we may conclude that the response time for the polar magnetic field to variations of the Y-component of the IMF is of the order 20 minutes.

Analysis of Sector Effects in the Polar Cap

When the sector polarity dependent polar cap variations were first discovered in the vertical component, it was also noted that at somewhat lower corrected geomagnetic latitudes (≈ 80°) the horizontal components showed opposite perturbations depending on the sector polarity. At Godhavn (77.5°N) the horizontal component is generally increased around noon during away sectors and decreased during toward sectors. To get a clearer picture of the nature of these polar cap variations, Svalgaard (1973a) analyzed data from nine stations in the northern hemisphere during the quiet year 1965. The geomagnetic field data was first converted to X, Y and Z components and then corrected for secular variation. All days with data gaps were excluded from the analysis. Diurnal variation curves of all three geomagnetic components were then computed for each IMF polarity (as observed by spacecraft) separately for the whole year. The average diurnal variations throughout the year were finally computed using all days.

Figure 6 shows the diurnal variation found for Z at Resolute Bay. The open circles display the variation found on days within away sectors (IMF Y component positive), while the solid dots show the average variation observed during towards sectors (IMF Y component negative). For about half of the day the sector polarity does not seem to have any marked influence on the value of the Z-component. However, during the other half of the day, roughly between 12^h and 24^h 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-component is decreased and reaches a minimum around 18^h UT, whereas on days with negative IMF polarity the Z-component is increased by about the same amount during the same interval of the day.

The average daily variation found by using all days of the year irrespective of sector polarity is shown by the dashed curve in Figure 6, demonstrating the almost complete cancellation of the sector polarity influence when about the same number of days with opposite IMF polarity are averaged together. In view of the detailed short-period dependence as shown in Figure 5, we would also expect this cancellation effect.

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 (or more strictly for a given sign of the azimuthal component), we find a certain deviation (taking place roughly between 12^h and 24^h UT in the northern hemisphere) from the simple sinusoidal daily variation for each magnetic element. For the opposite polarity about the same deviation is observed, but with the opposite sign. Figure 7 gives another example of the general behavior for the North (X) component at Resolute Bay. It seems as if the influence of the sector polarity is just superposed on the simple regular diurnal variation, and thus may be extracted by subtracting this sinusoidal variation from the observed diurnal variations. Examples of the result of the subtraction are given in the lower part of Figures 6 and 7.

Polar Cap Current System

Using the data and procedures discussed in the previous section, the nature of the influence of IMF on the high latitude geomagnetic field was studied by Svalgaard (1973a). The IMF effects over the northern polar cap were found to be strongest at 17^h - 19^h UT. At that time it is local noon over the northern magnetic pole, and conditions seem the most favorable for direct interactions between the solar wind and the polar cap field. From very high latitudes and down to about 75° the influence of the IMF sector structure was dominating over all other effects, whereas there were only very slight, if any, indications of any IMF polarity influence at auroral latitudes (below 70°). The effects are thus well confined to the interior of the polar cap and can hardly be interpreted as extensions of certain types of substorm activity. Kawasaki et al. (1973), analysing correlated short-period fluctuations of the two fields, also reached the conclusion that the effects depending on the sector polarity are not related to substorms.

A synoptic presentation of the IMF sector effects as observed at 18^h UT during away and toward sectors is given in Figure 8 and 9 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. Traditionally the Z- component is considered positive when directed downwards (i.e., towards the earth); however a Z-perturbation directed away from the earth decreases the magnitude of the vertical force in the northern polar cap, but increases it in the southern polar cap.

It is evident from Figures 8 and 9 that there is a clear systematic difference in the way the geomagnetic field is disturbed during conditions with opposite IMF polarities. For away IMF polarity (Figure 8) the horizontal perturbation vectors all converge towards the magnetic pole, and vertical perturbations directed away from the earth (negative in the northern hemisphere) are observed near the pole while vertical perturbations towards the earth (positive in northern hemisphere) are seen below 80° invariant latitude. For towards polarity (Figure 9) 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 counterclockwise for away IMF polarity and clockwise for toward polarity. The location and direction of this current (presumably a Hall current) is indicated in Figures 8 and 9. From an analysis of geomagnetic data from seven stations in the northern and eleven stations in the southern hemisphere, Mansurov and Mansurova (1971) deduced essentially the same current system to account for the polarity effects observed within the polar caps. However in the interpretation of the effect they tentatively concluded that the current only appeared in the northern hemisphere during away sectors and in the southern hemisphere during toward sectors only. It seems clear, however, from the detailed correlation between short-period variations in the polar field and the IMF that the correlation is present at all times during the day hours and is <u>not</u> restricted to a given polarity (away in the north, toward in the south).

The perturbations and currents shown in Figures 8 and 9 were derived by subtracting the all-day average field values at 18^h UT from the values observed for the two IMF polarities separately. If we instead compute the mean value of the field components over a day the regular sinusoidal diurnal variation will tend to cancel out, but the IMF polarity effects will remain and influence the mean value systematically depending on sector polarity.

The mean values of the three components (X, Y, Z), corrected for secular variation, were computed for nine northern stations by <u>Svalgaard</u> (1973a) for three samples of data through 1965: namely (i) for all days within away sectors, (ii) for all days within toward sectors, and (iii) for all days irrespective of the sector polarity. Subtracting the average field values for the last sample from the first two samples should then show any effects related to IMF polarity. Figure 10 shows the result plotted against invariant latitude. The IMF polarity effect in the Z-component is again characteristic 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^o invariant latitude suggesting that the current is nearly overhead at this latitude. The magnitude of perturbations of the horizontal component directed towards the invariant pole is shown in the lower part of Figure 10. The horizontal effects are strongest at about 82^o invariant latitude which is nearly where the Z-perturbations change sign.

Mansurov and Mansurova plotted the differences between the hourly mean centered at noon and the daily mean for the horizontal and vertical components. Their result for the southern hemisphere is shown in Figure 11. The mean for all days irrespective of sector polarity is shown by the dashed lines. Their figure is very much like Figure 10, which is for the northern hemisphere. Thus several methods of analysis all lead to the conclusion that the effect of the azimuthal component of the IMF on the geomagnetic field can be described as the magnetic effects of a current system encircling the magnetic poles at about 80° invariant latitude during the day hours. The current direction changes when the sign of the IMF azimuthal component changes.

Seasonal Variations of the Polar Cap Current

The magnitude of the influence of the IMF polarity on the polar geomagnetic field has a very pronounced seasonal variation, being largest during local summer. A simple measure of this change is the difference between seasonal averages of the Z-component close to the pole during toward sectors and the averages during away sectors for the same season. This seasonal difference of ΔZ for three polar caps stations is shown in Figure 12. The magnitude of the effect is very small (only a few gammas) during winter but increases sharply towards 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. There exists another seasonal effect in the time of maximum perturbation, which in the northern polar cap occurs earlier during the summer than during winter. Table 2 lists the time of maximum perturbation for five stations during different seasons. There is a progressive change towards 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 from Vostok in the south that this seasonal effect is reversed in the southern polar cap, so that time of maximum perturbation changes towards later hours from winter towards local summer. However, more study of this particular effect is needed before a definitive conclusion can be reached on this point.

Station	Winter	Equinox	Summer	Change	Geogr. Latitude
Alert	$18^{\mathrm{o}}.0$ UT	$14^{\mathrm{h}}.0$	$13^{\mathrm{h}}.0$ UT	$5^{\mathrm{h}}.0$	$82^{\mathrm{o}}.5$
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

Table 2. Seasonal variation of average time of maximum perturbation of polar cap geomagnetic field. The total change from winter to summer is also given together with the geographic latitude of the stations.

We have seen that significant daily and seasonal variations of the intensity of the polar cap current system exist; their nature suggests that ionospheric conductivity as well as magnetospheric geometry probably both play a role for the mechanism responsible for originating and maintaining the polar cap current system.

Even if the magnitude of the polar cap disturbances is small during winter, it is still possible to identify the signature of the IMF polarity, and therefore to infer the sector polarity. Part of the reason for this is that other disturbances tend to have small magnitudes too. It is however necessary to employ high sensitivity, temperature compensated magnetographs. Comparisons between the list of inferred polarities published by Svalgaard (1972) and the polarities measured by spacecraft (Wilcox and Colburn, 1972) made separately for the summer half-year and for the winter half-year, show very little difference in the accuracy of the inferred polarities. The accuracy of the inferred polarity is only 3% lower during winter than during summer. Also, Heckman et al. (1973) compared the polarity inferred from Thule during local winter with that inferred from Vostok which then had local summer and found very few cases of disagreements, so one can conclude that in spite of the large seasonal variation of the IMF polarity effect, it is generally possible to identify the effect almost independent of its magnitude.

Physical Cause of the Polar Cap Current

The existence of the polar cap current system is a challenge to our present understanding of magnetospheric physics, according to which the polar cap current ought not to be there at all. The very direct polar cap response to changes in the IMF polarity and also the direct access of solar flare particles to the polar caps strongly suggests that we are dealing with an open magnetosphere, where reconnection of geomagnetic and interplanetary field lines is important. The details of this reconnection process are not well understood, and in addition our understanding of the situation is hampered by the difficulty of simply mentally visualizing the resulting three-dimensional field line configuration.

In a qualitative analysis of the general properties of an open magnetosphere Stern (1973) examined the topological effects of reconnection between the geomagnetic field and an interplanetary azimuthal magnetic field. After all, the large-scale interplanetary magnetic field is oriented approximately perpendicular to the earth's dipole axis rather than parallel to it. Stern's model is able to explain: (i) a rather uniform dawn to dusk polar cap electric field including (ii) the IMF polarity dependent asymmetry observed by Heppner, and (iii) an ionospheric polar cap current changing direction when the IMF polarity changes, and finally (iv) the familiar two-celled magnetospheric convection pattern with return flow at sub-polar cap latitudes. It may well be that Stern's model of the open magnetosphere is a significant step towards the kind of models we will be working with in the future.

In Stern's model there exist four types of field lines – closed field lines starting and ending on the earth, open lines connected to the northern polar cap, open lines connected to the southern polar cap and unlinked field lines with no connection to the dipole. Similarly, space may be divided into four regions, each containing only field lines of one type. Already Dungey showed that in models of this type the four regions generally meet along a line, called by Stern the <u>separatrix</u>. The separatrix is not a neutral line but has a field direction always pointing from south to north. Figure 13 shows the geometry of the model as seen from the sun for the two cases of interplanetary field polarity. The critical point in Stern's model is now that interplanetary field lines when brought out to earth by the solar wind will be swept some distance along the separatrix before breaking loose and connecting with polar field lines.

Far in space there exists a constant electric field along the vertical axis of Figure 13. Thus the electric field across the polar cap, assuming that the magnetic field lines are equipotentials, should be quite uniform. However, if the separatrix does have a field direction along it, it exerts a sweeping effect, most pronounced for field lines that impinge near the boundary of the polar cap: these are swept towards the northernmost neutral point and their ends on earth are swept towards the points to which the neutral points are connected. Therefore the equipotentials become distorted and bent along the polar cap boundary.

This situation is shown in Figure 14. The left hand pattern corresponds to polar equipotentials with no sweeping effect along the separatrix. The pattern on the right corresponds to southern polar cap for an away sector. If the external field is reversed – corresponding to a toward sector – the patterns also reverse as indicated on the figure. So while the electric field in the center of the polar cap is always from dawn to dusk, the sweeping effect of the separatrix results in a structural property which is opposite in the two polar caps and which also reverses when the azimuthal component of the interplanetary field reverses. This is precisely what is required to explain the magnetic observations in the polar caps. The nested, crescent-shaped equipotentials are roughly aligned with the polar cap boundary, so that with enough ionospheric conductivity a Pedersen current will flow orthogonal to the boundary, but the Hall current, which is larger and therefore more important in producing magnetic variations, will run along the boundary. It is easily seen from Figure 14 that the Hall current has opposite directions for the two IMF polarities in the correct sense to enable one to identify it with the circulating polar cap current deduced from magnetic observations.

Solar Physics and Polar Geomagnetic Observations

The relation between the polarity of the interplanetary magnetic field and the polar field of the earth is one of the most direct solar-terrestrial relationships known. The effect is always there; it is usually very clear and sharp, and it is literally connected with the fundamental agent of solar activity: the solar magnetic field. Even in the space-age it shows the importance of using the earth itself as an Interplanetary Monitoring Platform. Polar geomagnetic observations have been carried out for most of the present century, and therefore it has been possible to infer the sector polarity for each day back to 1926 using magnetograms from Godhavn (Svalgaard, 1972). The interplanetary magnetic field structure is very similar to the large-scale solar photospheric magnetic field (Severny et al., 1970). The availability of the inferred field polarities over the past five sunspot cycles could add significantly to our knowledge of the sun and the solar cycle.

One such application of the inferred field was the confirmation by Wilcox and Scherrer (1972) of a suggestion by Rosenberg and

Coleman that when the earth is north of the solar equatorial plane the IMF should be biased by the polarity of the northern magnetic pole of the sun and by the southern pole when the earth is south of the solar equator. It was even possible to show that the polar regions of the sun change polarity two to three years after sunspot maximum on the average, something which has only been directly observed one or maybe two times.

When the interplanetary sector structure was first discovered during the declining phase of sunspot cycle #19 there were four stable sectors. Solar activity in the next cycle tended to obscure the regular sector pattern and the IMF showed an evolving character. Now, in the declining portion of the present cycle a stable four-sector pattern is again observed (Figure 15). Analysis of the inferred field shows (Svalgaard, 1973b) that this four-sector pattern is a persistent feature of at least the last five sunspot cycles and that it is most clearly observed for about three years prior to sunspot minimum. This together with other evidences hint towards a higher degree of organization of the solar magnetic field than would follow from the classical picture of solar magnetism.

The solar sector structure has proved to be a useful frame for organizing both solar activity and terrestrial responses to it. Since the structure is quasistable there are good prospects for short-term forecasting of both solar and terrestrial events if the evolution of the solar magnetic sector structure could be monitored on a real-time basis. The effect reviewed in this paper — the influence of the sector polarity on polar cap currents — is already being used for practical forecasting purposes at the Space Environment Services Center in Boulder, Colorado, in the United States and at the IZMIRAN near Moscow in the Soviet Union (Heckman et al., 1973). Geomagnetic data from Thule and from Vostok are transmitted in near real-time to the two forecast centers allowing them to infer the sector polarity and to keep track of changes in the sector structure with very short notice.

With the completion of the Stanford Solar Observatory, which is dedicated to observing the large-scale solar magnetic field, it should even be possible to observe a sector boundary on the sun up to a week before it reaches the earth. Going back in time, the many decades of polar geomagnetic observations can now be used to probe the secrets of the solar cycle and to show us new aspects of the magnetosphere and the polar cap ionosphere by demonstrating a new and very direct solar-terrestrial relationship: the continuous linkage of the magnetic field of the earth with that of the sun.

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Figure Captions

Figure 1. Average daily variation of 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. The dashed curve shows the corresponding 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 regular daily variation of the horizontal components. The approximate invariant latitude for the four stations used is given below:

A	Alert	86°.4 N
T	Thule	86.2
R	Resolute Bay	83.7
M	Mould Bay	81.2

(After Svalgaard, 1973a).

Figure 2. Sample Z-magnetograms from (a) away sector and (b) toward sector showing typical daily variations of the polar geomagnetic field observed at Vostok (84°.9 S) and Thule (86°.2 N). The arrows point to the quiet undisturbed level. (After Svalgaard, 1972).

Figure 3. Interplanetary magnetic field polarity (away from or towards the sun) during 1969 plotted on a chart of magnetic three-hour index *Kp* (after J. Bartels). Light shading is field polarity away from the sun, and dark shading is field polarity toward the sun. The top bar on each line represents the interplanetary magnetic field polarity observed with the Ames Research Center magnetometer on the spacecraft Explorers 33 and 35, and the bottom (narrower) bar on each line represents the field polarity inferred from observations of the polar cap geomagnetic field. The shading with horizontal lines represents intervals of mixed field polarity. (After *Friis-Christensen et al.*, 1971).

Figure 4. Hourly mean values of the Z component ($> 56000\ \gamma$) at Thule at 1600-1700 UT versus the hourly mean values at 1500-1600 UT of the components of the interplanetary magnetic field during June-August 1969: (a) eastward component BYM, (b) sunward component BXM, and (c) N-S component BZM. (After *Friis-Christensen et al.*, 1972).

Figure 5. Comparison of Thule Z-magnetograms with the azimuthal (Y) component of the interplanetary magnetic field in the solar ecliptic (SE) coordinate system observed by the IMP-3 satellite for several days during northern local summer. The Thule Z component (dotted line) is plotted positive downward. (Adapted after *Kawasaki et al.*, 1973).

Figure 6. Daily variations 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 magnetic field pointing away from the sun. Filled 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. (After Svalgaard, 1973a).

Figure 7. Daily variation of the North component at Resolute Bay for 1965. The format is the same as used in Figure 6. (After Svalgaard, 1973a).

Figure 8. Synoptic map of polar cap magnetic perturbations at 1800 UT during IMF away polarity. Horizontal perturbations are shown as vectors attached to 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 current which may produce the magnetic perturbations is indicated on the figure. (After Svalgaard, 1973a).

Figure 9. Same as Figure 8, but for IMF toward polarity. The direction of all perturbations is reversed compared to the situation found during away sectors, and the polar cap current is

also reversed. The position of the geographical pole (GP) and of the invariant magnetic pole (MP) are shown in both figures. (After Svalgaard, 1973a).

Figure 10. Difference between the yearly mean of Z and H for both IMF polarities and the all-day average values for 1965. The differences are plotted against invariant latitude for nine stations at high northern latitudes. Open circles are used for away polarity values and solid circles for toward polarity. (After Svalgaard, 1973a).

Figure 11. Differences between the hourly means of the horizontal component, X', pointing towards the corrected magnetic pole, and of the vertical component both centered at noon and the daily mean values. The data are from local summer in the southern hemisphere. The mean difference for all days irrespective of sector polarity is shown by the dashed lines. (Adapted after Mansurov and Mansurova, 1972).

Figure 12. Seasonal variation of the magnitude of the polar cap perturbations related to the IMF polarity. The effect is largest during local summer (S), smaller during the equinoxes (E), and smallest during winter (W). (After Svalgaard, 1973a).

Figure 13. Schematic view of the field of a dipole immersed in a constant field orthogonal to its axis, with the solar wind blowing into the plane of the figure. At the left is the situation for an external field parallel to the Y-axis, and

at the right for an external field antiparallel to the Y-axis. These two cases correspond to an away and toward polarity of the IMF respectively. The separatrix is also shown schematically (see text). (After Stern, 1972).

Figure 14. Schematic view of polar cap equipotentials for (left) no sweeping along the separatrix, (middle) with field lines shifted towards the dusk side (B), and (right) with field lines swept along the separatrix towards the dawn side (A). The patterns corresponding to opposing polar caps and external field directions are indicated on the figure. (After Stern, 1972).

Figure 15. Inferred interplanetary magnetic sector structure 1970-1972. For each day in the 27-day Bartels rotations the dominant IMF polarity is marked. Towards days are indicated by large filled circles, away days with a small dot; days with ambiguous or mixed field are marked by a cross. A large toward sector is prominent in the right hand side of the figure, while a less clear toward sector may be seen from about day 6 to day 12 in most rotations.

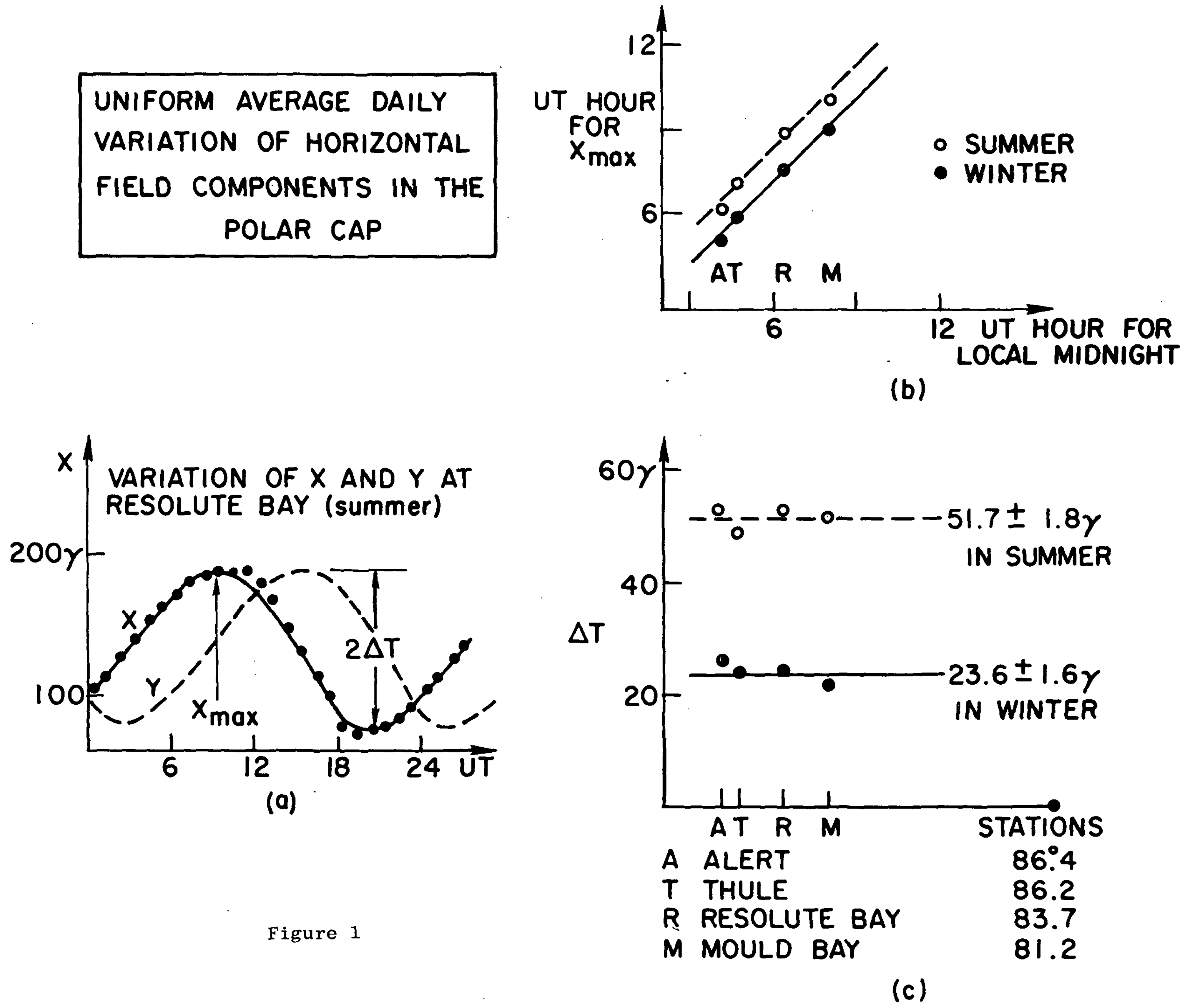
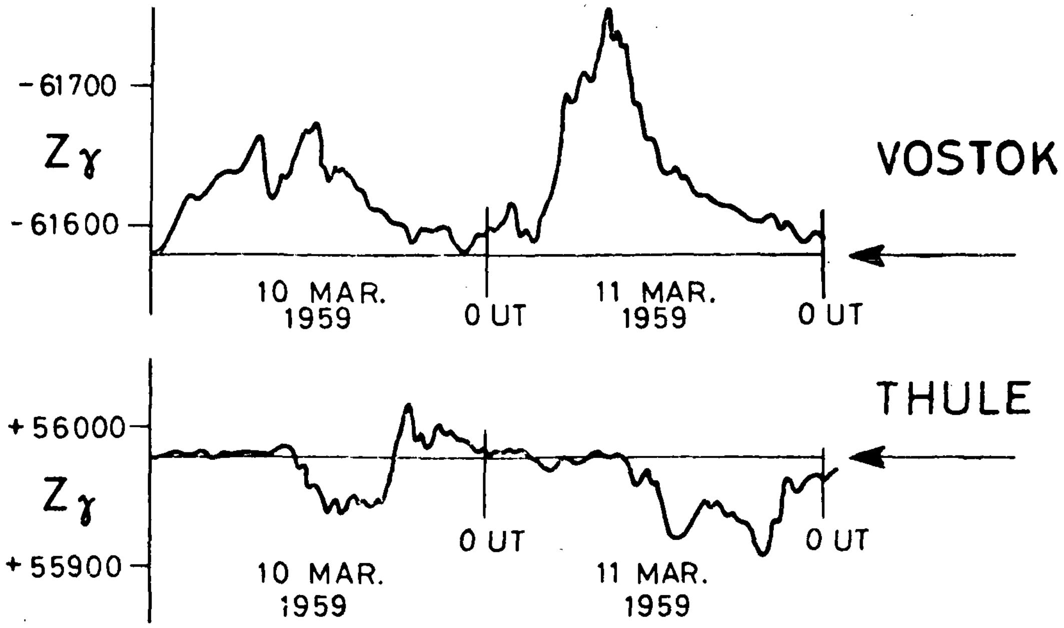
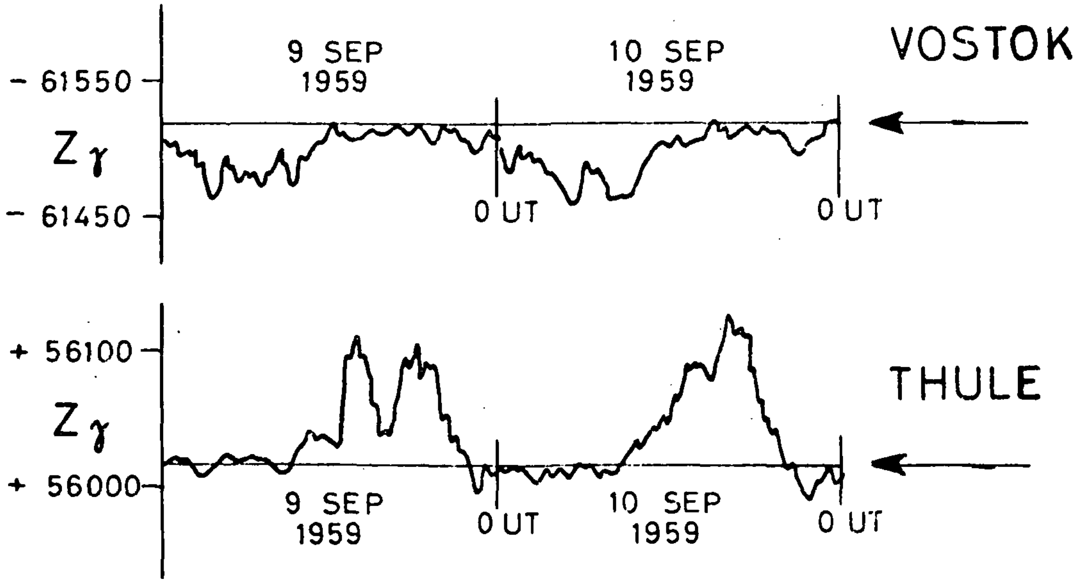

UNIFORM AVERAGE DAILY VARIATION OF HORIZONTAL FIELD COMPONENTS IN THE POLAR CAP
X
VARIATION OF X AND Y AT RESOLUTE BAY (summer)
200γ
100
X
Y
Xmax
2ΔT
6
12
18
24
UT
(a)
12
6
UT HOUR FOR Xmax
○ SUMMER
● WINTER
AT
R
M
6
12
UT HOUR FOR LOCAL MIDNIGHT
(b)
60γ
40
20
ΔT
51.7 ± 1.8γ IN SUMMER
23.6 ± 1.6γ IN WINTER
AT
R
M
STATIONS
A ALERT 86°4
T THULE 86.2
R RESOLUTE BAY 83.7
M MOULD BAY 81.2
(c)

Figure 1



Sample magnetograms from away sector



Sample magnetograms from toward sector

Figure 2

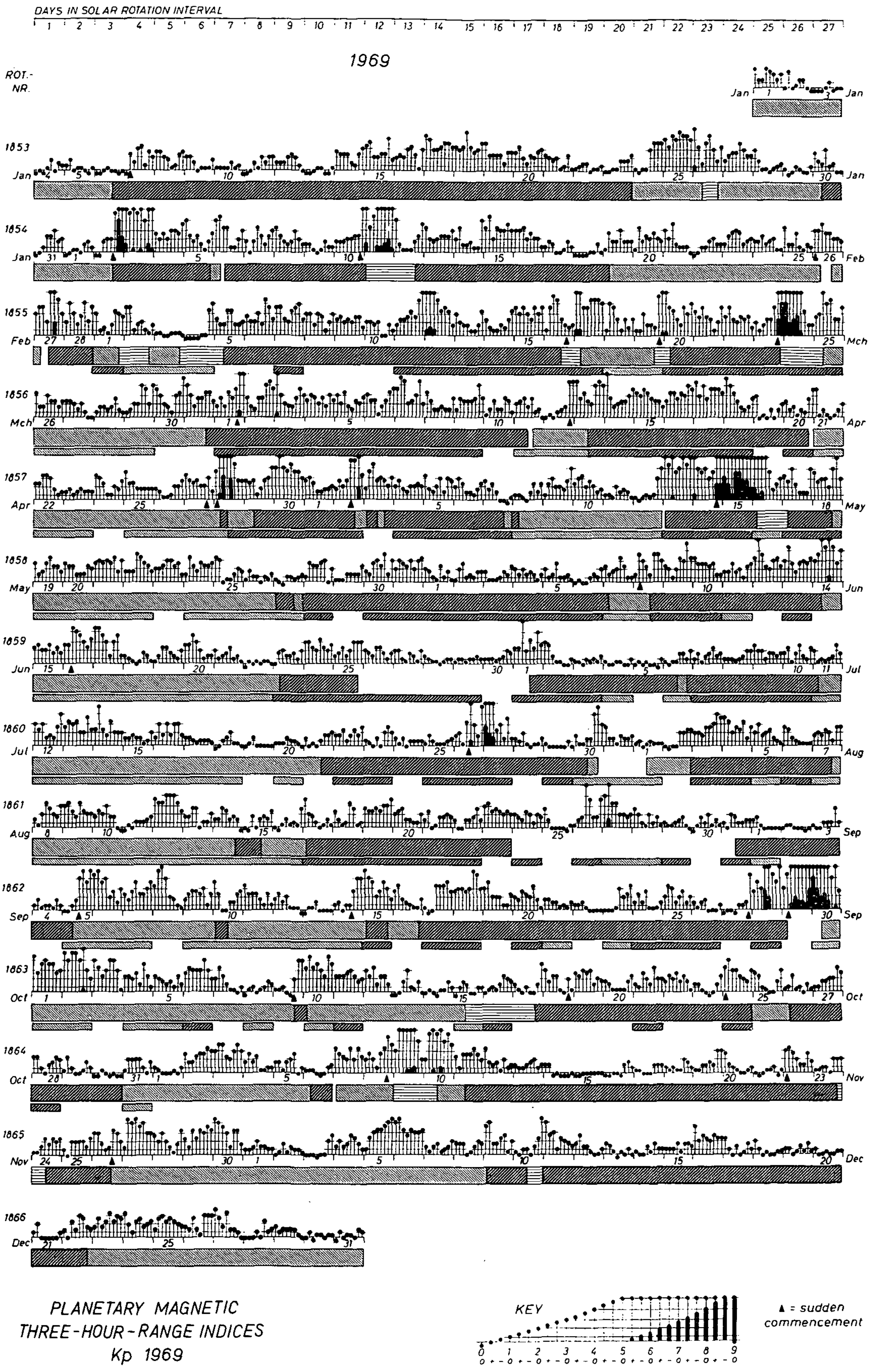

DAYS IN SOLAR ROTATION INTERVAL
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27
1969
ROT.-NR.
Jan 1 3 Jan
1853 Jan 4 5 10 15 20 25 30 Jan
1854 Jan 31 1 5 10 15 20 25 26 Feb
1855 Feb 27 28 1 5 10 15 20 25 Mch
1856 Mch 26 30 1 5 10 15 20 21 Apr
1857 Apr 22 25 30 1 5 10 15 18 May
1858 May 19 20 25 30 1 5 10 14 Jun
1859 Jun 15 20 25 30 1 5 10 11 Jul
1860 Jul 12 15 20 25 30 1 5 7 Aug
1861 Aug 8 10 15 20 25 30 1 3 Sep
1862 Sep 4 5 10 15 20 25 30 Sep
1863 Oct 1 5 10 15 20 25 27 Oct
1864 Oct 28 31 1 5 10 15 20 23 Nov
1865 Nov 24 25 30 1 5 10 15 20 Dec
1866 Dec 21 25 31
PLANETARY MAGNETIC
THREE-HOUR-RANGE INDICES
Kp 1969
KEY
0 1 2 3 4 5 6 7 8 9
0 + - 0 + - 0 + - 0 + - 0 + - 0 + - 0 + - 0 + - 0 + - 0
▲ = sudden commencement

Figure 3

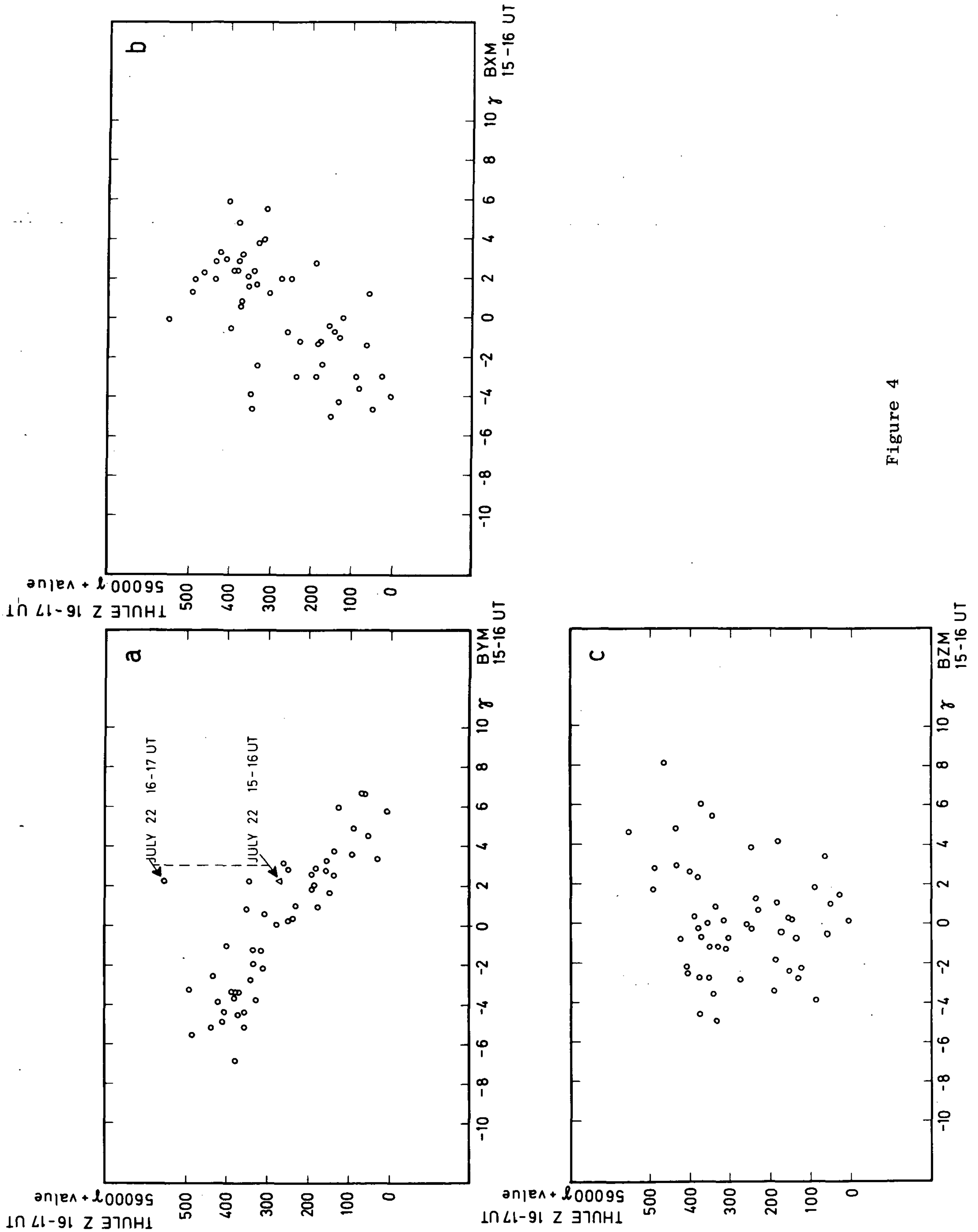
a
b
C
THULE Z 16-17 UT
56000γ + value
500
400
300
200
100
0
BYM 15-16 UT
BXM 15-16 UT
BZM 15-16 UT
-10
-8
-6
-4
-2
0
2
4
6
8
10 γ
JULY 22 16-17 UT
JULY 22 15-16 UT

Figure 4

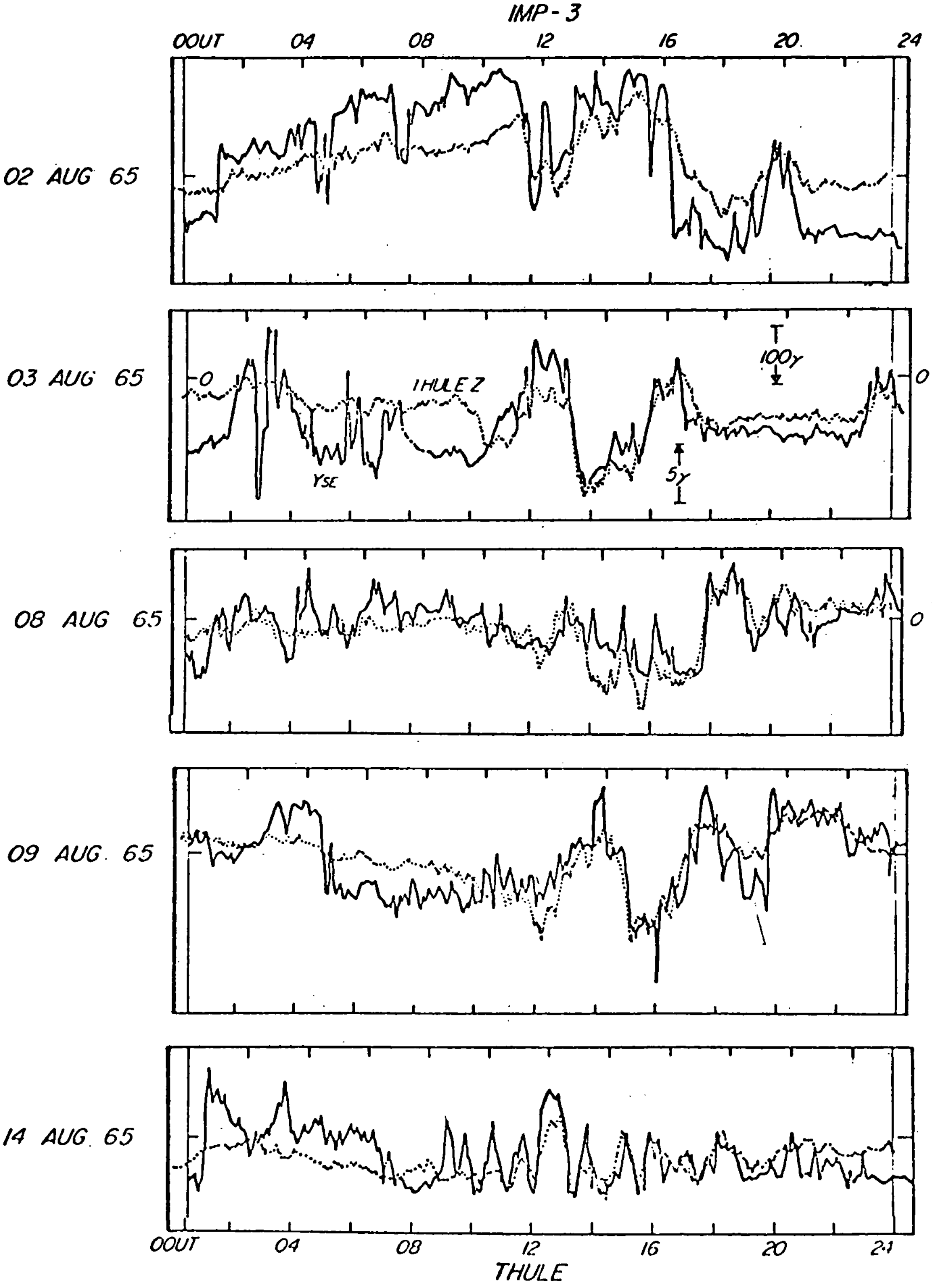

IMP-3
00UT
04
08
12
16
20
24
02 AUG 65
03 AUG 65
0
THULE Z
YSE
100γ
5γ
0
08 AUG 65
0
09 AUG 65
14 AUG 65
00UT
04
08
12
16
20
24
THULE

Figure 5

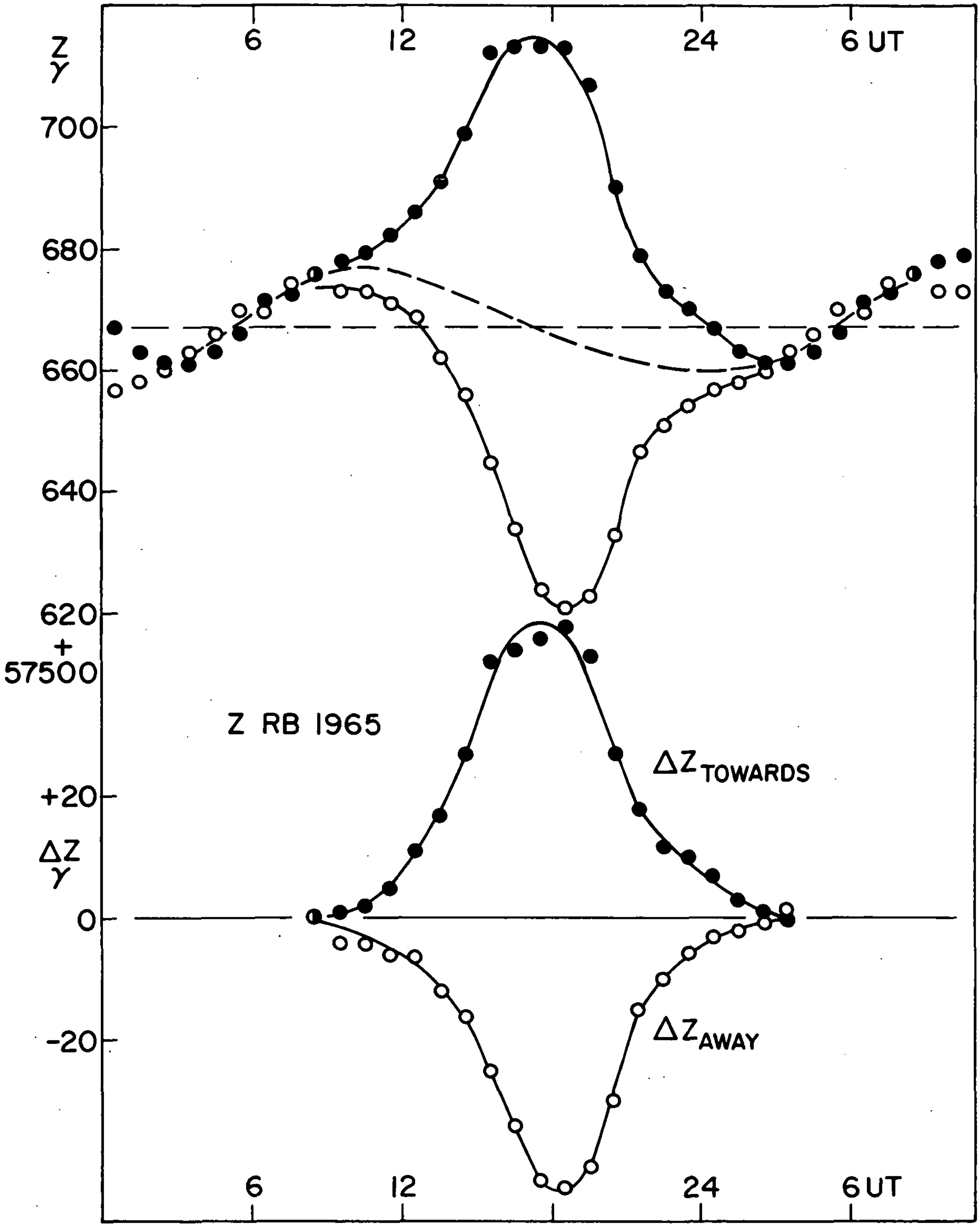

Z
γ
6
12
24
6 UT
700
680
660
640
620
+
57500
Z RB 1965
+20
ΔZ
γ
0
-20
ΔZ_TOWARDS
ΔZ_AWAY
6
12
24
6 UT

Figure 6

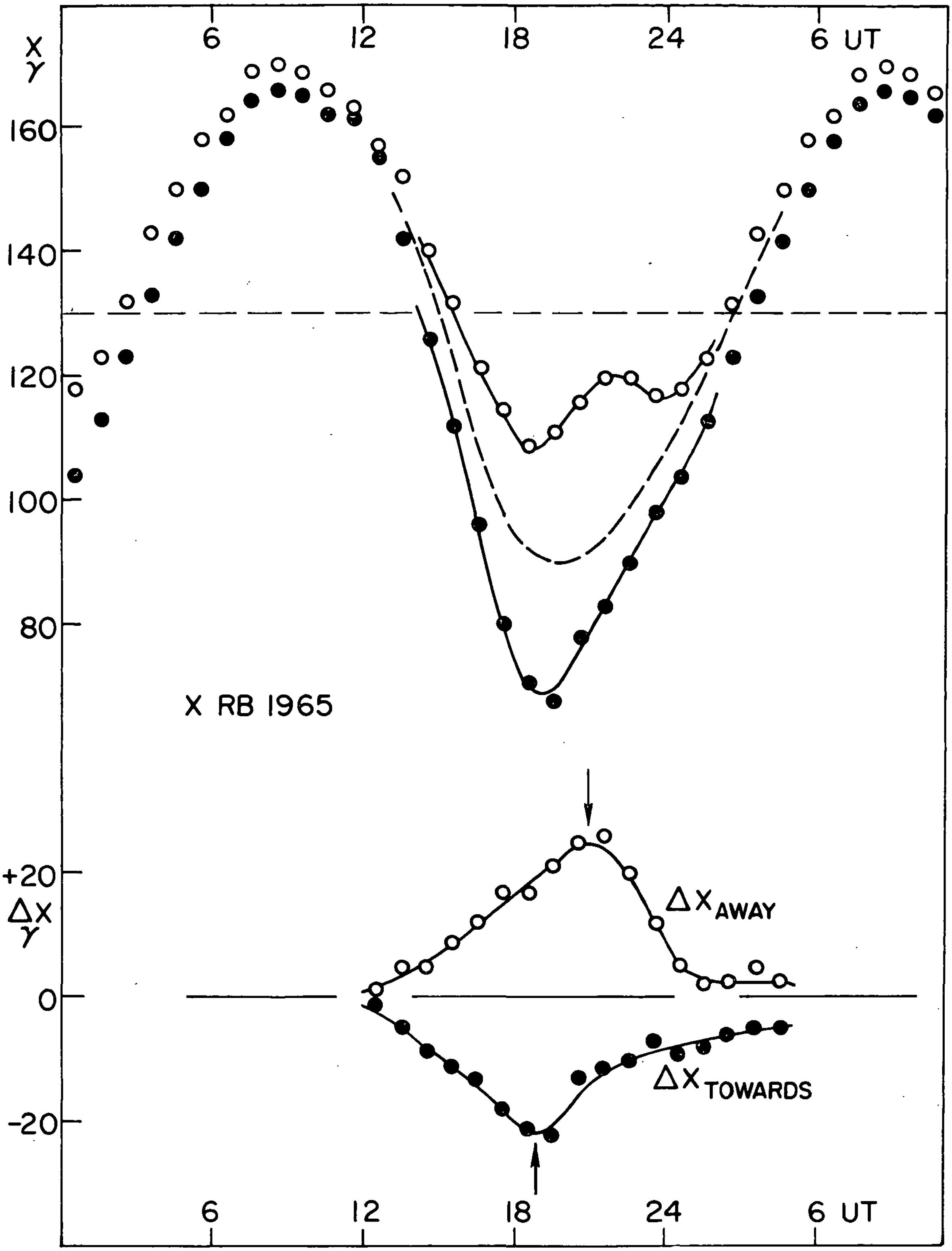
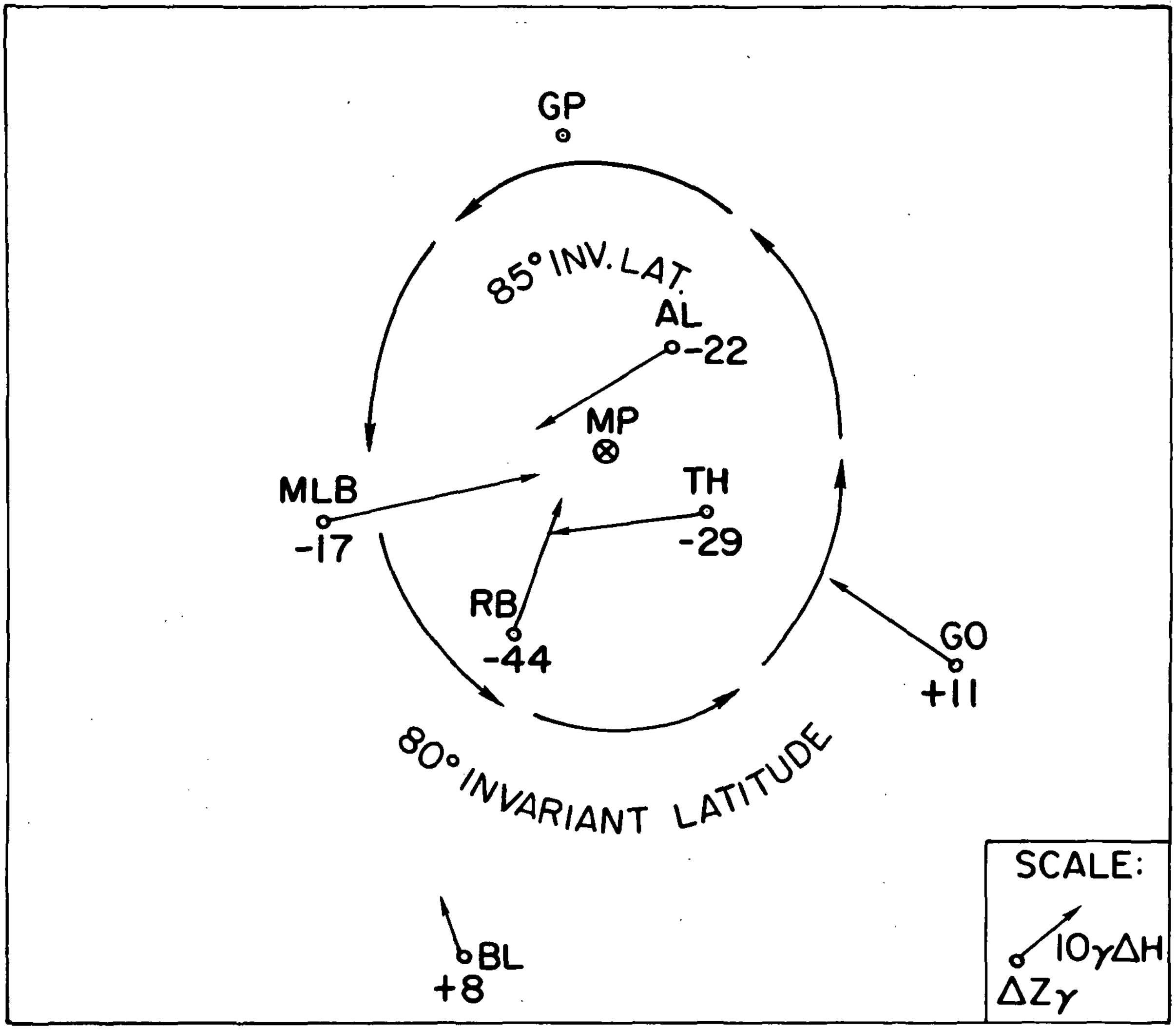
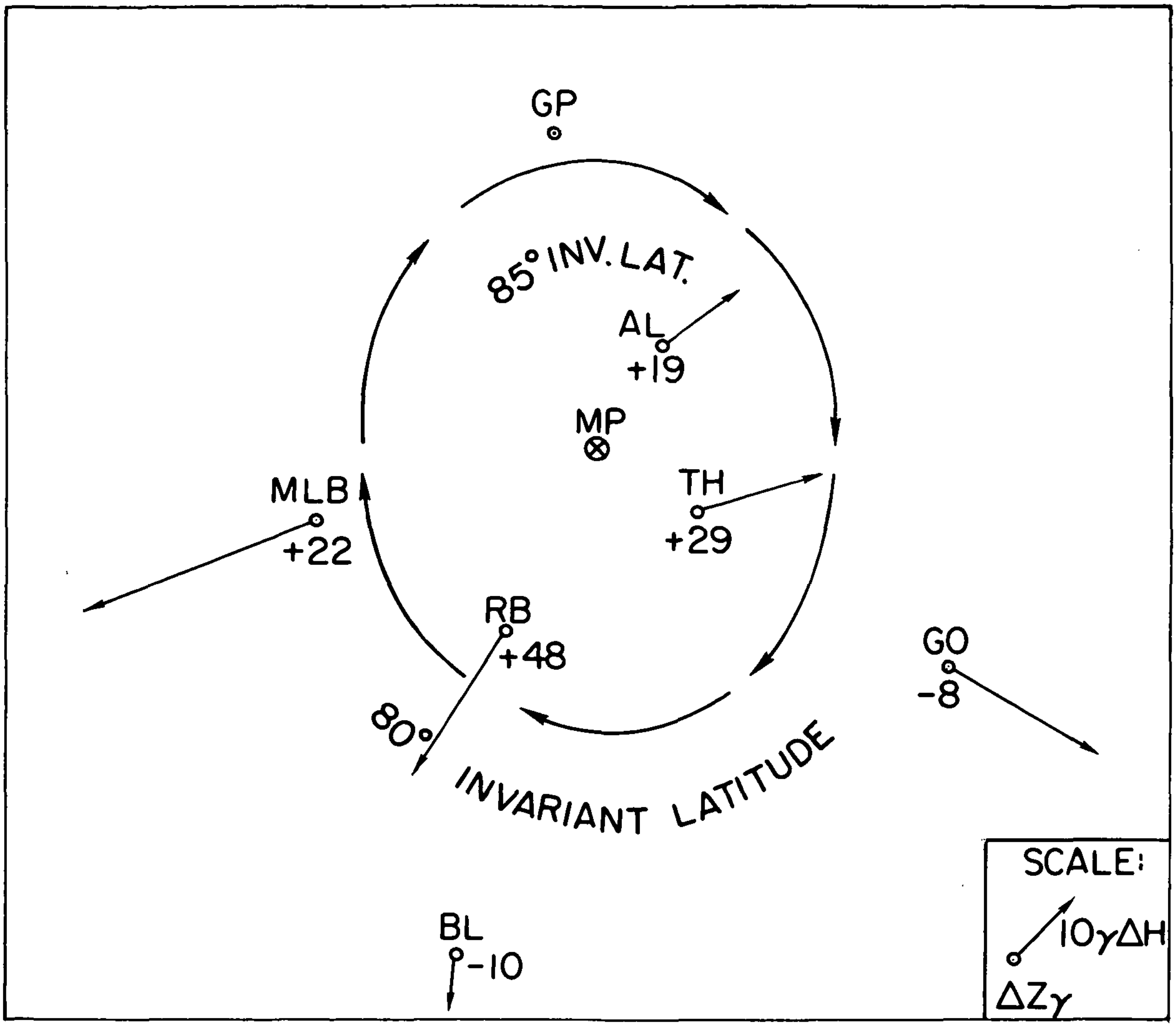

X
γ
160
140
120
100
80
6
12
18
24
6 UT
X RB 1965
+20
ΔX
γ
0
-20
ΔX AWAY
ΔX TOWARDS
6
12
18
24
6 UT

Figure 7



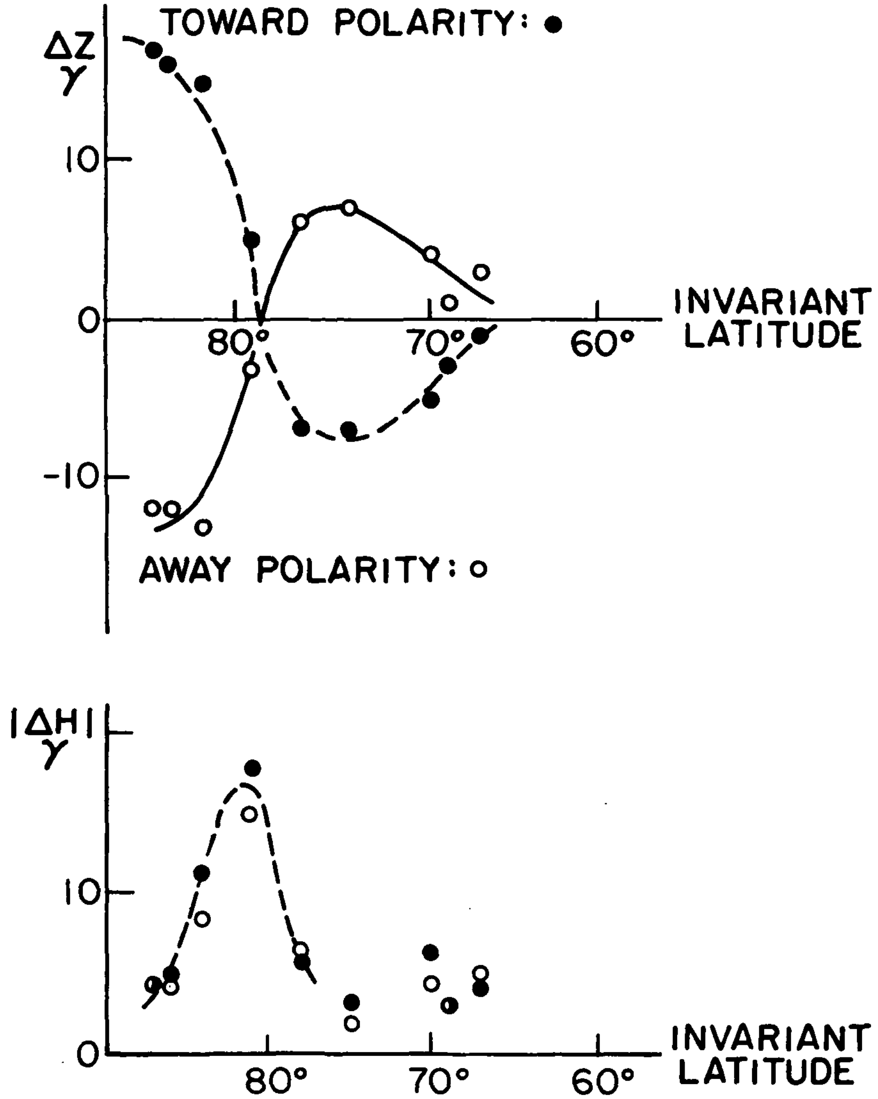
POLAR CAP DISTURBANCES AT 18^h UT FOUND DURING IMF AWAY POLARITY. A CIRCULATING IONOSPHERIC HALL CURRENT FLOWING EASTWARD AROUND THE MAGNETIC POLE (MP) FITS THE OBSERVATIONS.

Figure 8



POLAR CAP DISTURBANCES AT 18^h UT FOUND DURING IMF TOWARD POLARITY. A CIRCULATING IONOSPHERIC HALL CURRENT FLOWING WESTWARD AROUND THE MAGNETIC POLE (MP) FITS THE OBSERVATIONS.

Figure 9



YEARLY AVERAGES OF POLAR CAP DISTURBANCE SHOWN SEPARATELY FOR EACH POLARITY OF THE INTERPLANETARY MAGNETIC FIELD.

Figure 10

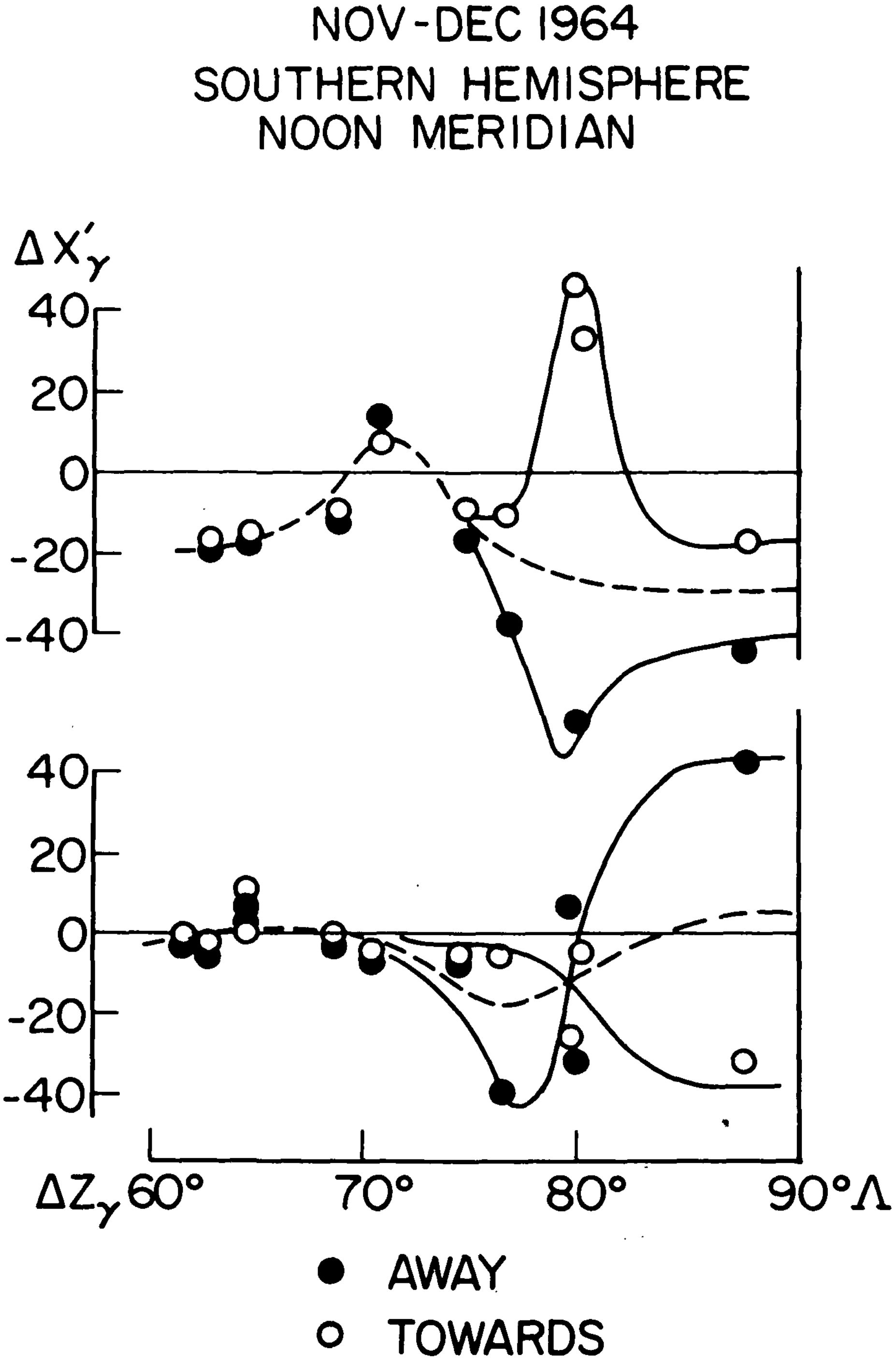
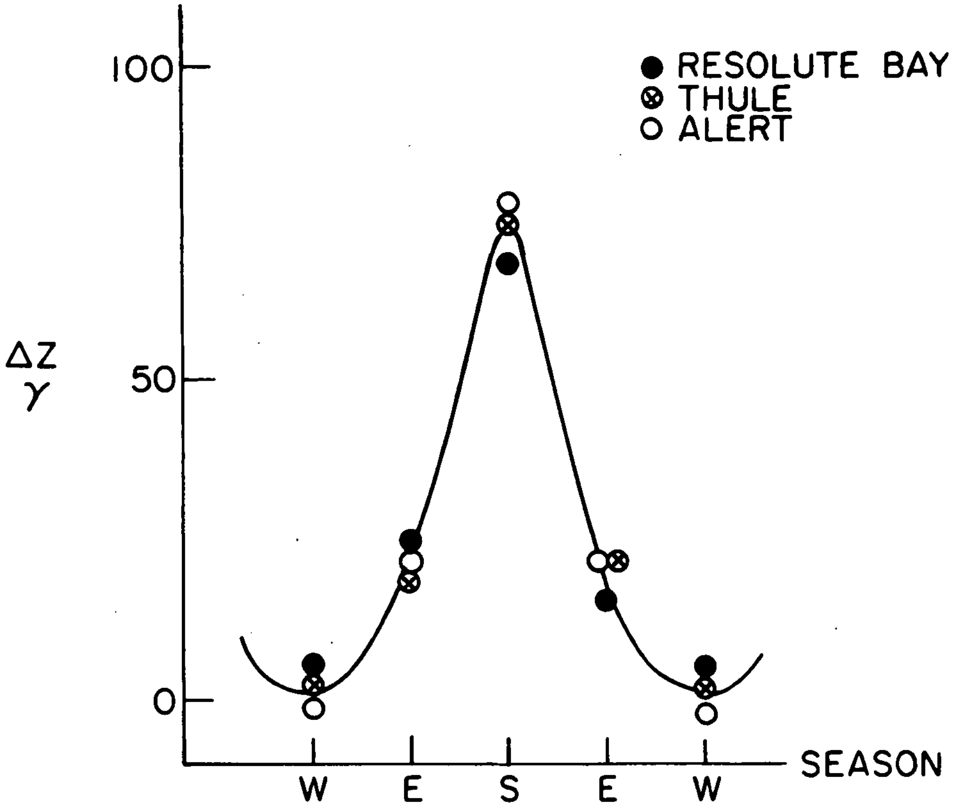

NOV-DEC 1964
SOUTHERN HEMISPHERE
NOON MERIDIAN
$\Delta X'_\gamma$
40
20
0
-20
-40
40
20
0
-20
-40
ΔZ_γ
60°
70°
80°
90°Λ
● AWAY
○ TOWARDS

Figure 11



MAGNITUDE OF THE POLARITY EFFECT IN THE POLAR CAP.

Figure 12

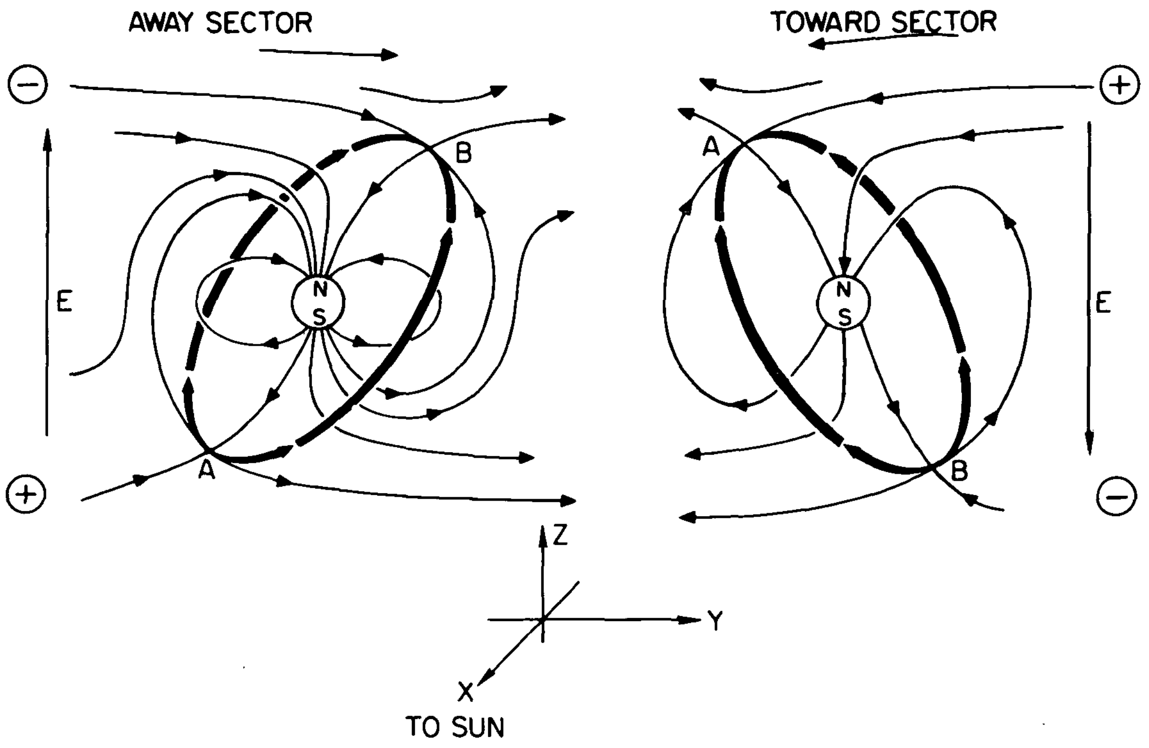


Figure 13

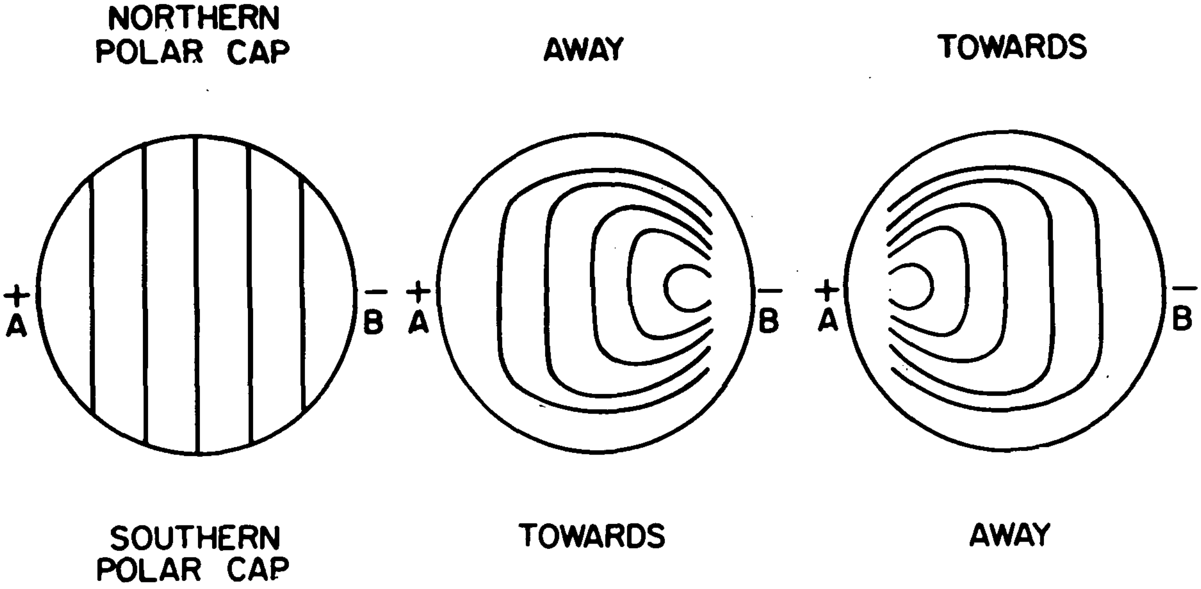

NORTHERN POLAR CAP
AWAY
TOWARDS
+ A
− B
+ A
− B
+ A
− B
SOUTHERN POLAR CAP
TOWARDS
AWAY

Figure 14

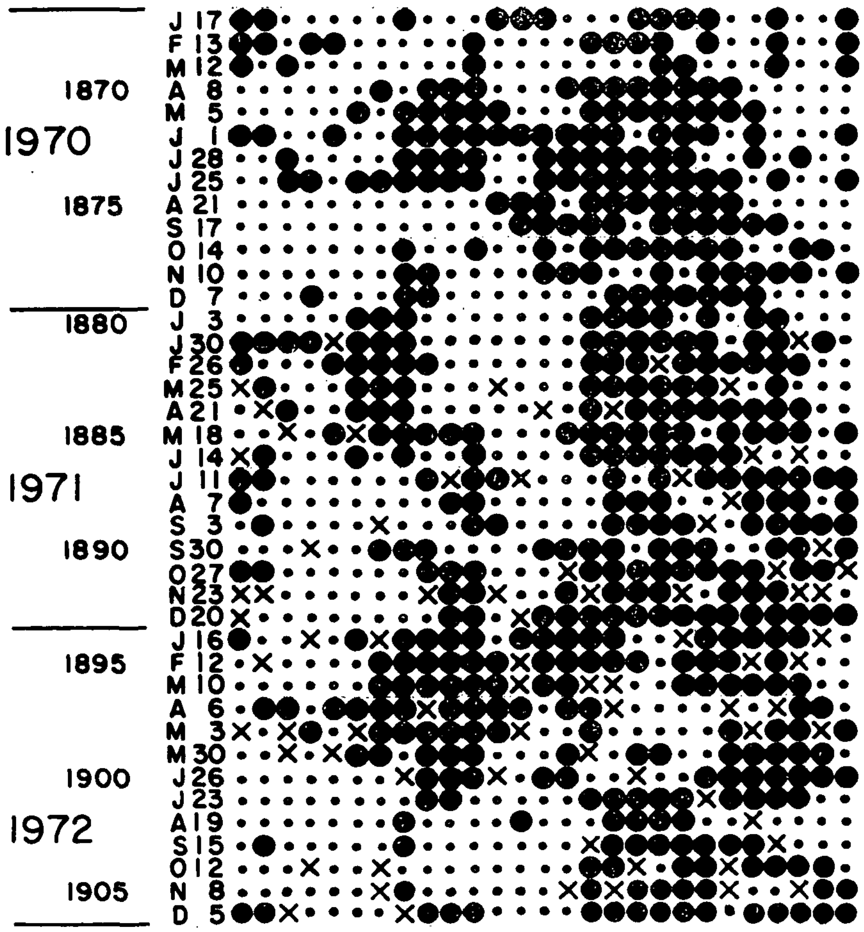

1870
1970
1875
1880
1885
1971
1890
1895
1900
1972
1905
J 17
F 13
M 12
A 8
M 5
J 1
J 28
J 25
A 21
S 17
O 14
N 10
D 7
J 3
J 30
F 26
M 25
A 21
M 18
J 14
J 11
A 7
S 3
S 30
O 27
N 23
D 20
J 16
F 12
M 10
A 6
M 3
M 30
J 26
J 23
A 19
S 15
O 12
N 8
D 5

Figure 15

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13. ABSTRACT

The recently discovered relation between the azimuthal component of the interplanetary magnetic field and magnetic variations in the earth's polar caps is reviewed. When the IMF azimuthal component is positive (typical of an interplanetary sector with magnetic field directed away from the sun) geomagnetic perturbations directed away from the earth are observed within 8° from the corrected geomagnetic pole. When the IMF azimuthal component is negative (typically within toward sectors) the geomagnetic perturbations are directed towards the earth at both poles. These perturbations can also be described by an equivalent current flowing at a constant magnetic latitude of 80°-82° clockwise around the magnetic poles during towards sectors and counterclockwise during away sectors. This current fluctuates in magnitude and direction with the azimuthal component of the IMF, with a delay time of the order of 20 minutes. The importance of this effect for our understanding of both solar magnetism and magnetospheric physics is stressed in view of the possibility for investigating the solar sector structure during the last five sunspot cycles.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
POLAR CAP CURRENTS						
INTERPLANETARY MAGNETIC FIELD						