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High-Latitude Electric Fields and the Three-Dimensional Interaction Between the Interplanetary and Terrestrial Magnetic Fields

F. S. MOZER, W. D. GONZALEZ,[1] F. BOGOTT, M. C. KELLEY, AND S. SCHUTZ

Physics Department and Space Sciences Laboratory
University of California, Berkeley, California 94720

More than 200 hours of ionospheric electric field measurements taken on balloons flown from three polar cap sites have been analyzed to determine average properties of the large-scale polar cap electric field and its dependencies on the interplanetary magnetic field. The major component of this electric field was directed from dawn to dusk and produced an average polar cap potential drop of about 55 kV. The magnitude of this potential provides an upper limit of about 700 R_E for the length of the magnetospheric tail and implies an energy input from the solar wind to the magnetosphere of about 5×10^{19} ergs/sec. The dawn to dusk component of the high-latitude polar cap electric field responds to B_z, the northward component of the interplanetary magnetic field, on a time scale $\lesssim 1$ hour and with an average increase of about 3 mV/m for each 1 γ decrease of B_z. The hourly averages of the electric field data at each of the three sites are well described by a two-cell convection pattern whose location depends on the y component of the interplanetary magnetic field. When B_y is positive (negative), the two-cell convection pattern shifts toward dawn (dusk) in the northern hemisphere with the following consequences: the maximum intensity of the northern polar cap dawn to dusk electric field component occurs at local morning (evening), and the auroral zone return flow reaches higher latitudes in the evening (morning). Evidence of the vector nature of the interaction between interplanetary and terrestrial magnetic fields is provided by the observation that the above B_y dependent signatures are most evident when B_z is most negative.

The fundamental character of large-scale magnetospheric convection might best be elucidated through measurements of polar cap electric fields. Because of the importance of such convection to magnetospheric dynamics [*Dungey,* 1961; *Axford and Hines,* 1961; *Obayashi and Nishida,* 1968; *Coroniti and Kennel,* 1972] and because at least one recent model [*Frank,* 1971] assumes a convection pattern different from the antisolar polar cap flow of the two-cell pattern of earlier theories [*Axford,* 1969], measurements of the ionospheric polar cap electric field have been undertaken with balloon-borne electric field detectors.

Many observations of the influence of the N-S component of the interplanetary magnetic field on the earth's magnetic field suggest that most substorm-related events are a result of this influence. Recent work has also shown the influence of the azimuthal component of the interplanetary magnetic field on the earth's magnetic field at high latitudes, through polar cap geomagnetic variations observed by ground magnetometers [*Svalgaard,* 1968; *Mansurov,* 1969; *Friis-Christensen et al.,* 1971, 1972; *Kawasaki et al.,* 1972; *Berthelier and Guerin,* 1972] and asymmetries in polar cap convection [*Heppner,* 1972]. Thus there is experimental evidence that the interplanetary magnetic field interacts with the terrestrial magnetic field as a vector, each of whose components can affect the transfer of energy to the magnetosphere. This paper presents further evidence of the vector nature of this interaction through analyses of the polar cap ionospheric electric field data and associates this interaction with general characteristics of magnetic field reconnection between the interplanetary and terrestrial magnetic fields [*Dungey,* 1953, 1961; *Sweet,* 1958; *Parker,* 1963; *Petschek,* 1964; *Axford,* 1967; *Yeh and Axford,* 1970; *Brátenahl,* 1971; *Coppi and Friedland,* 1971].

DISCUSSION OF THE EXPERIMENTAL DATA

Three balloons were flown from each of three polar cap sites in early September 1971 to measure ionospheric electric fields by a technique that is described elsewhere [*Mozer and Serlin,* 1969; *Mozer,* 1971*a*]. Fifteen-minute averages of electric field components perpendicular to the magnetic field lines and pointing from dawn to dusk and from sun to tail, as measured in a rotating frame of reference, are presented in Figures 1 and 2. The magnetic latitudes of the launch sites were Cambridge Bay, Canada, 78°; Resolute Bay, Canada, 84°; and Thule, Greenland, 87°. Three hours of data obtained at Resolute Bay early on September 7 are plotted at the beginning of September 3 in Figures 1 and 2.

Average values of the electric field data of Figures 1 and 2, along with those obtained in 1969 from Cambridge Bay [*Mozer and Manka,* 1971], are presented in Table 1 as computed in a frame of reference fixed to the earth's orbital motion but not to its diurnal rotation. In the following discussion of the averages of Table 1, the data from Cambridge Bay will be omitted since, as will be shown below, this site was often outside the polar cap during the measurement interval.

The average value of the instantaneous magnitude of the polar cap electric field was about 30 mV/m. This field pointed largely in the dawn to dusk direction, since this component

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[1] Also at the Institute for Plasma Research, Stanford University, Stanford, California 94305.

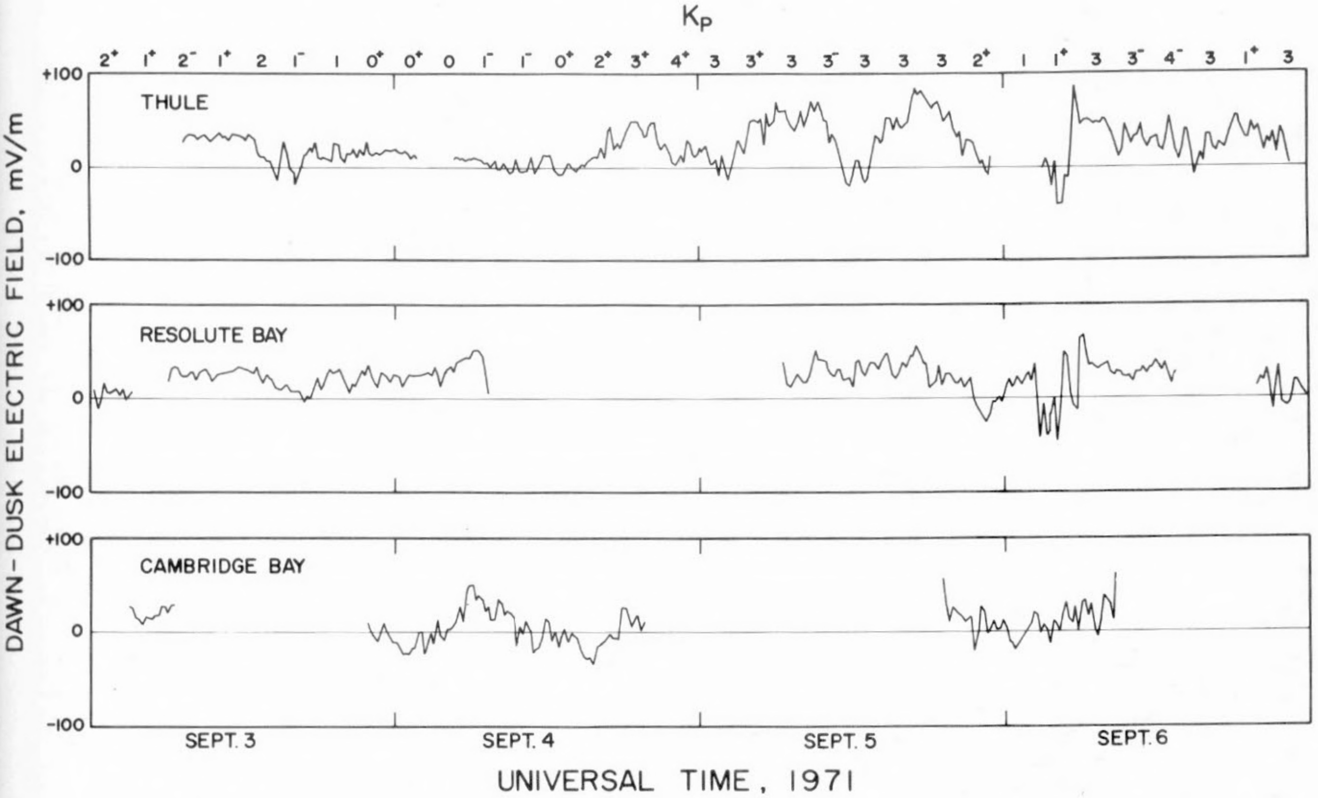

Fig. 1. Fifteen-minute averages of the dawn to dusk component of the ionospheric electric field measured in a rotating frame of reference on nine balloons.

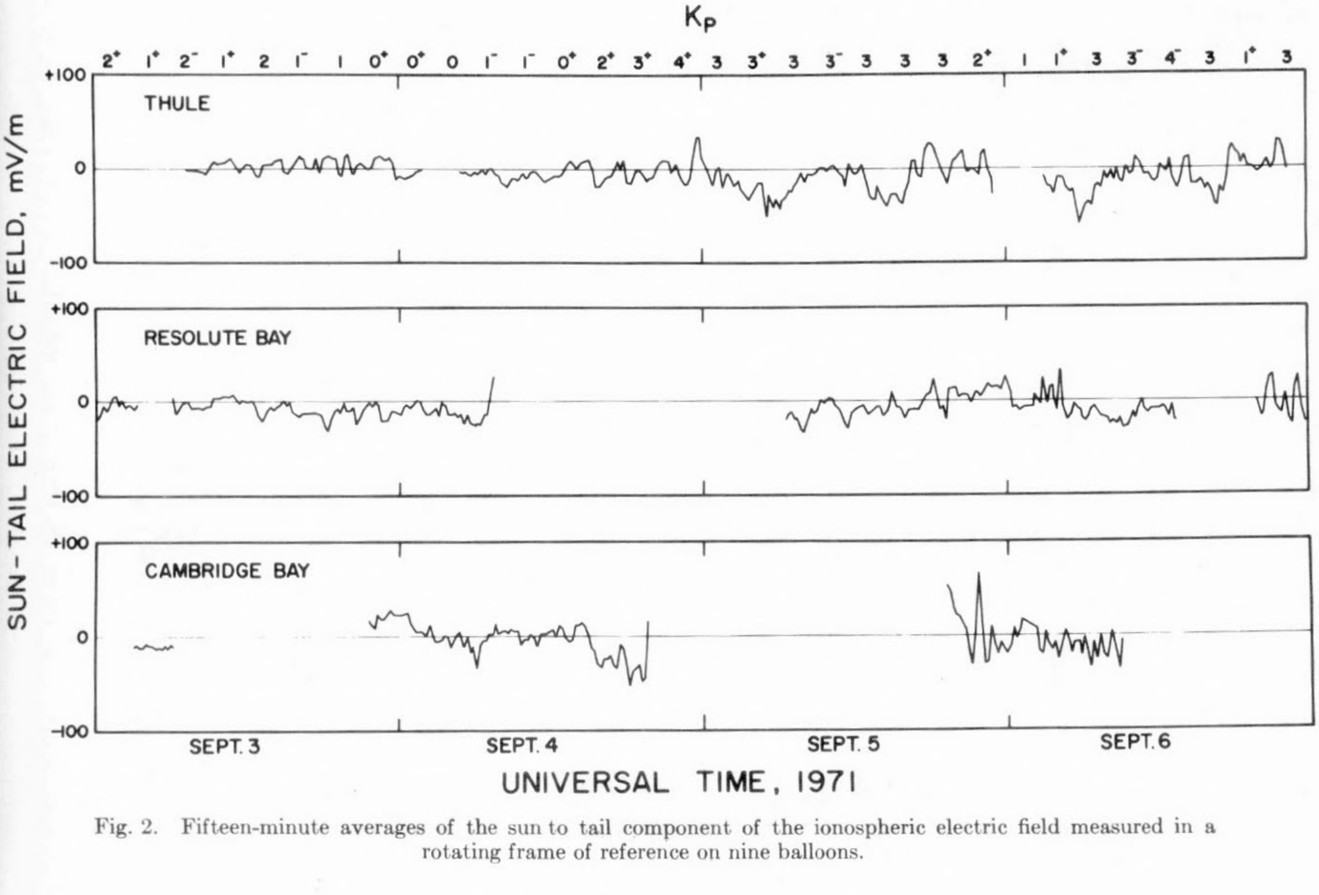

Fig. 2. Fifteen-minute averages of the sun to tail component of the ionospheric electric field measured in a rotating frame of reference on nine balloons.

TABLE 1. Averages of the Polar Cap Electric Field Data

Site	Hours of Data	$\langle E_{\mathrm{inst}} \rangle$, mV/m	$\langle E_{\mathrm{DD}} \rangle$, mV/m	$\langle E_{\mathrm{ST}} \rangle$, mV/m	Flow Angle, deg
Thule	84	30.8	22.2	−3.3	8.5
Resolute Bay	67	29.2	18.0	−7.1	21.5
Cambridge Bay	76	22.2	5.0	−3.8	27.5
Total	227	27.5	15.2	−4.6	17

had an average value of about 20 mV/m, which corresponds to a polar cap potential drop of about 55 kV. That the field magnitude obtained from the means of the components was only about 70% of the average of the instantaneous field magnitudes is due to fluctuations in the local field, which are also present in lower-latitude measurements [*Mozer and Manka*, 1971; *Mozer*, 1971*b*]. The average **E × B** flow across the polar cap deviated from the antisolar direction by roughly 15°. About half this deviation is accounted for by the aberration of the flow due to the earth's orbital motion around the sun, and the rest could be caused by deviations of the solar wind flow from the radial direction during the measurement interval.

The data of Figures 1 and 2 are combined in Figure 3 to estimate the large-scale polar cap electric field from plots of electric field vectors obtained from the average of each hour of data from each site. Figure 3 is drawn in a geomagnetic latitude–magnetic local time nonrotating frame of reference fixed to the earth. The vectors without arrow heads at the lowest latitude site, Cambridge Bay, are obtained from the flights in August 1969.

The level of fluctuations in the average field magnitude and direction, as well as general properties of the average field, are indicated by the spread of the vectors of Figure 3. For example, the general dawn to dusk direction of the high-latitude field is apparent even though individual 1-hour averages, such as that near 1930 at Resolute Bay, may point in opposite directions. It is also noted that every one of 22 hourly averages of the electric field measured at Cambridge Bay between 0200 and 1000 had a dawn to dusk component that pointed toward dawn. Thus Cambridge Bay was outside the polar cap region of antisolar convection in the early morning during the entire measurement interval. This behavior is probably associated with the direction of the interplanetary magnetic field, as will be discussed below.

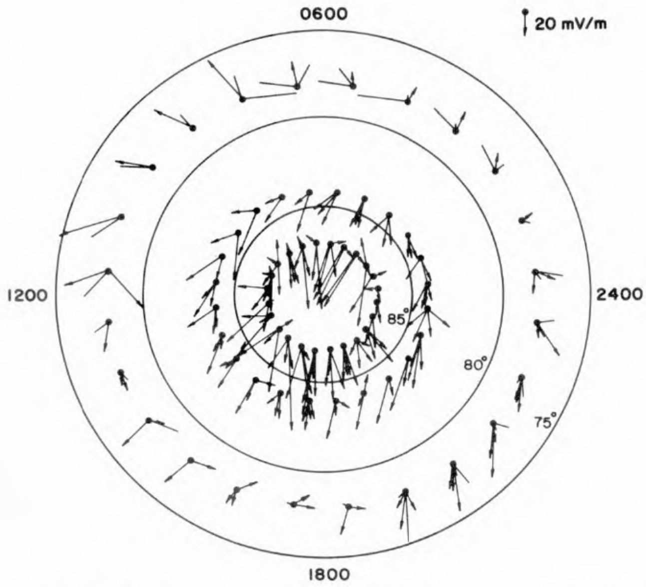

Fig. 3. One-hour average electric field vectors plotted in a geomagnetic latitude–magnetic local time nonrotating frame of reference.

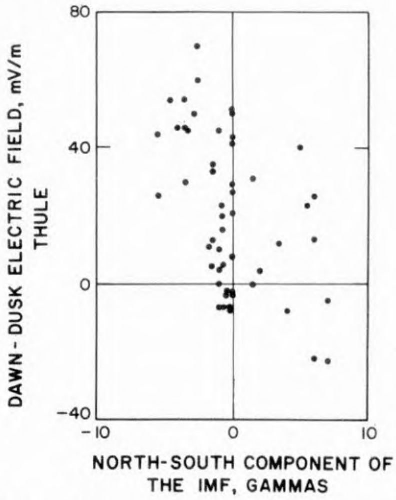

Fig. 4. Scatter plot of the hourly average values of the dawn to dusk electric field component observed at Thule and the northward component of the interplanetary magnetic field measured during the same hour.

INFLUENCE OF THE NORTH-SOUTH COMPONENT OF THE INTERPLANETARY MAGNETIC FIELD

The polar cap electric field data obtained at Thule and Resolute Bay have been used to illustrate the correlation between the north-south component of the interplanetary magnetic field and the dawn-dusk component of the ionospheric electric field [*Mozer and Gonzalez*, 1973]. This correlation will be investigated further by considering 1-hour averages of the electric field plotted versus the average over the same hour of the *z* component of the interplanetary magnetic field in solar magnetospheric coord-

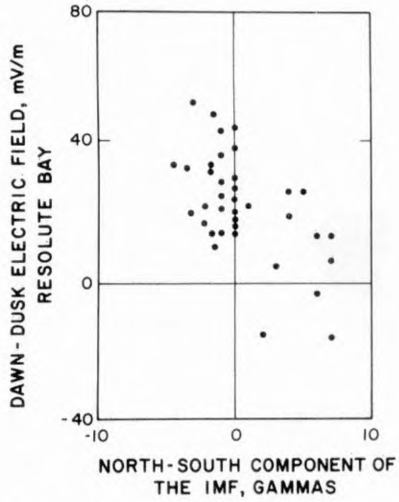

Fig. 5. Scatter plot of the hourly average values of the dawn to dusk electric field component observed at Resolute Bay and the northward component of the interplanetary magnetic field measured during the same hour.

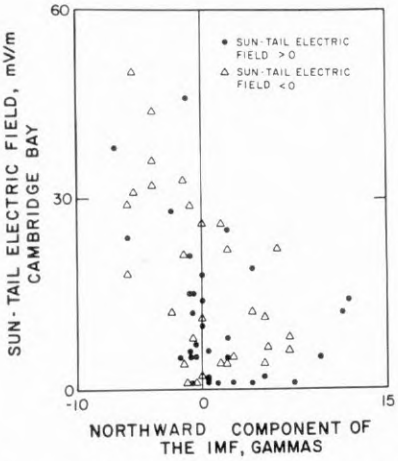

Fig. 6. Scatter plot of the hourly average values of the sun to tail electric field component observed at Cambridge Bay and the northward component of the interplanetary magnetic field measured during the same hour.

nates for those times when interplanetary field data were available (D. Fairfield, private communication, 1972). The results, plotted in Figures 4, 5, and 6, illustrate the tendency for the ionospheric electric field to be larger when the interplanetary magnetic field is large and southward. This result is in disagreement with recent satellite measurements in which no such correlation was observed [*Heppner*, 1972]. The spread of the points in these figures from the mean behavior given by the least squares fit, E (mV/m) $= 22 - 3B_z$ (gammas), may be due both to local fluctuations and the influence of other components of the interplanetary magnetic field.

Because of the disagreement between the above conclusions and those reached from satellite electric field data and because the relationship between the southward component of the interplanetary magnetic field and the polar cap electric fields is crucial to reconnection theories, the present data have been examined to verify the validity of the apparent relationship. As a first test the southward component of the interplanetary magnetic field was correlated with other magnetic field components during the observation interval, and no significant correlations were found. Therefore whatever effects are present in Figures 4, 5, and 6 are probably due to the southward interplanetary field component. To study the significance of the relationship seen in these figures, the correlation coefficient between the polar ionospheric electric field and the northward interplanetary magnetic field has been computed for several assumed time delays between the two measurements. The results, shown in Figure 7, show a correlation that peaks near zero time delay and that is sufficiently large to suggest that the observed relationship is real. A further conclusion from Figure 7 is that the time delay between changes of the north-south component of the interplanetary magnetic field and the polar cap ionospheric electric field is $\lesssim 1$ hour. Since this time is comparable to the propagation time of Alfvén waves from the dayside neutral point to the polar cap ionosphere, there is some experimental evidence for the direct communication of magnetopause electric fields to the polar ionosphere. The open magnetosphere geometry implied by these results is in agreement with trajectory calculations for and observations of solar particle entry into the polar caps along open field lines [*Morfill and Quenby*, 1971; *Evans and Stone*, 1972; Stone, private communication, 1973].

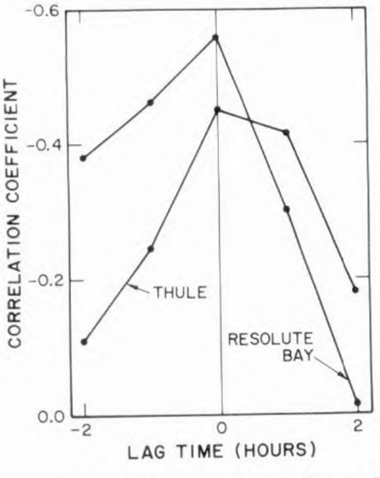

Fig. 7. Correlation coefficient of the linear least squares fit to the scatter plot of the dawn-dusk component of the ionospheric electric field measured at Thule and Resolute Bay versus the x component of the interplanetary magnetic field.

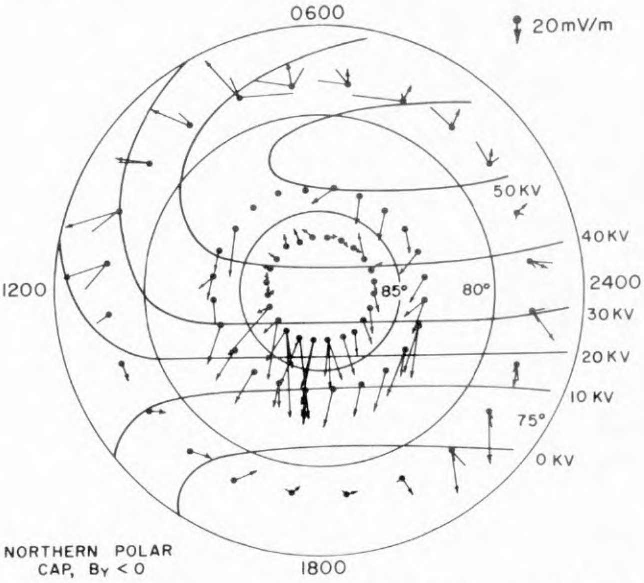

Fig. 8. Hourly average electric field vectors plotted in a magnetic local time-invariant latitude nonrotating frame of reference for the data collected when $B_y < 0$, along with equipotential contours of the large-scale polar cap electric field deduced from the experimental data. Several vectors emanating from a point mean that samples were collected on more than 1 day.

Influence of the Azimuthal Component of the Interplanetary Magnetic Field

In Figures 8 and 9 one-hour averages of the measured electric field vectors are plotted in a magnetic local time–invariant latitude nonrotating frame of reference for the two cases of $B_y < 0$ and $B_y > 0$. Polar cap electric equipotentials are also shown as estimated from the experimental data, and the assumption that the variation of the equipotential contours with the sign of B_y involves only inversion of the prenoon and afternoon contours. These figures indicate a shift of the two-cell convection pattern toward

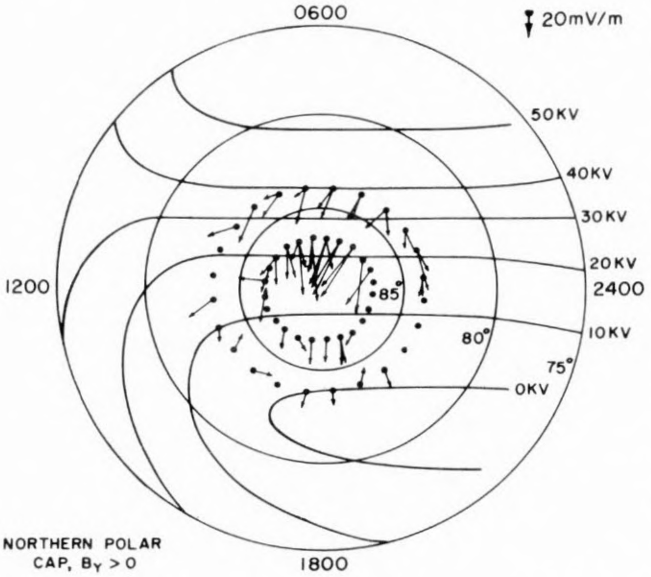

Fig. 9. Hourly average electric field vectors plotted in a magnetic local time–invariant latitude nonrotating frame of reference for the data collected when $B_y > 0$, along with equipotential contours of the large-scale polar cap electric field deduced in Figure 8 and inverted. Several vectors emanating from a point mean that samples were collected on more than 1 day.

morning (evening) when $B_y > 0$ ($B_y < 0$). This shift is also observed in the average auroral zone electric field [*Mozer and Lucht*, 1974].

The apparent shift of the two-cell convection pattern should cause the dawn to dusk component of the electric field to be a maximum in the local morning (evening) when $B_y > 0$ ($B_y < 0$). To test this possibility, Figures 10 and 11 present plots of the hourly averages of the electric field components at Thule and Resolute Bay, subdivided into the two cases of positive or negative y component of the same hourly average of the interplanetary magnetic field. Electric field data for which this magnetic field component was near zero or not measured have been deleted from these plots, and some estimates of the interplanetary field polarity have been based on high-latitude ground magnetograms. The agreement between the direction of the azimuthal component of the interplanetary magnetic field and the morning or afternoon location of the maximum in the dawn to dusk electric field is clear evidence of reconnection between this component of the interplanetary magnetic field and the terrestrial magnetic field. Electric field data from a polar orbiting satellite have also shown this relationship [*Heppner*, 1972].

Because of the apparent shift of the two-cell convection pattern with the sign of B_y, the sunward return convection should reach higher latitudes in the evening (morning) when $B_y > 0$ ($B_y < 0$). Figure 12 presents the low-latitude polar cap electric field data obtained at Cambridge Bay. The y component of the interplanetary magnetic field was mostly negative for the periods of observation, and the observed minimum of the dawn to dusk component at local morning agrees with expectations.

Ionospheric Hall currents flow along the equipotential contours of Figures 8 and 9 in a direction from the tail toward the sun. These zonal currents cause positive Z

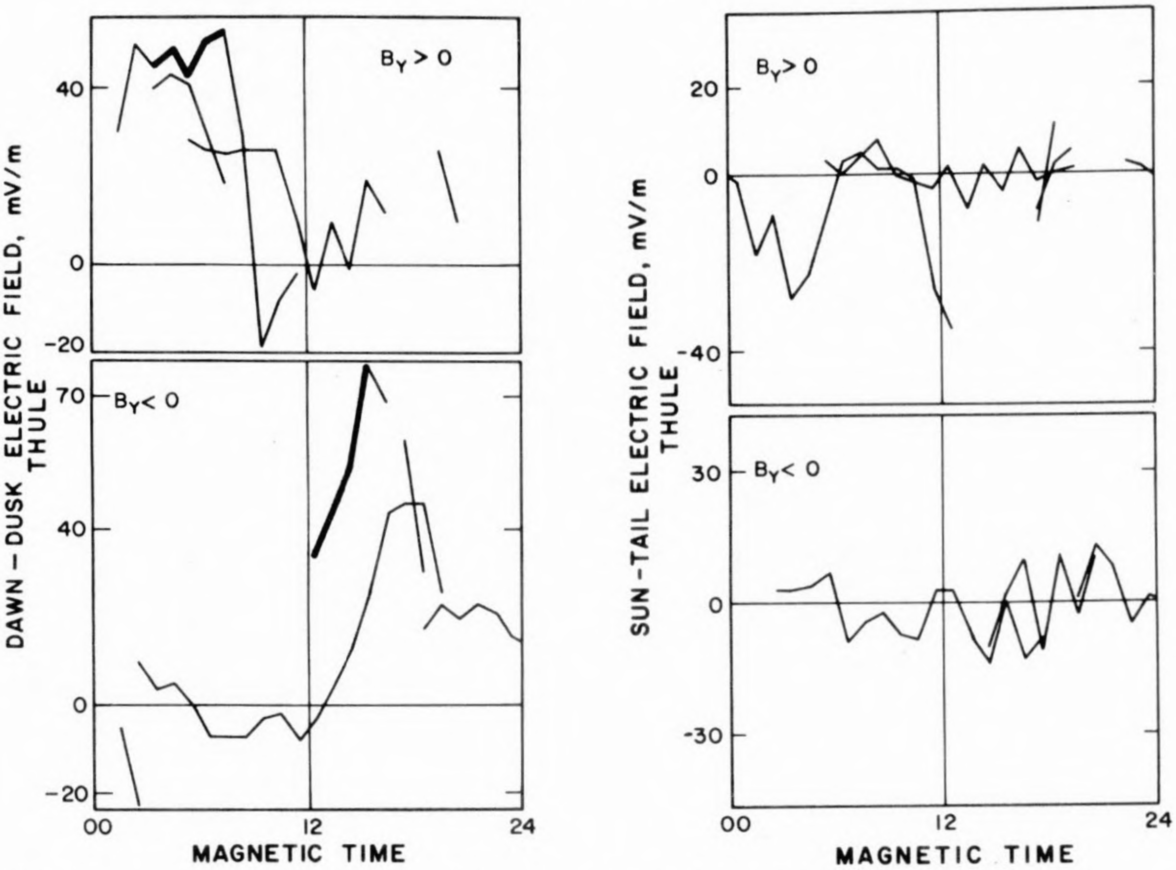

Fig. 10. Hourly averages of the electric field components measured at Thule in a nonrotating frame of reference for $B_y > 0$ and $B_y < 0$.

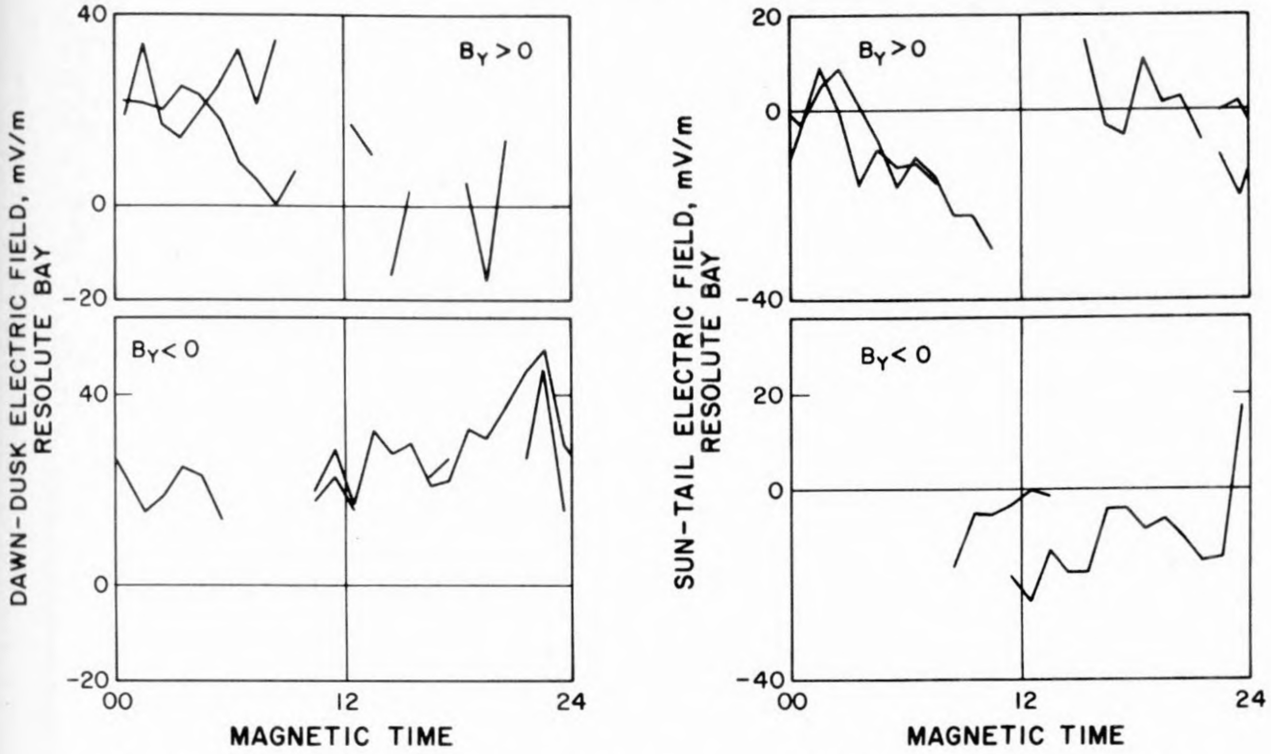

Fig. 11. Hourly averages of the electric field components measured at Resolute Bay in a nonrotating frame of reference for $B_y > 0$ and $B_y < 0$.

deviations in ground magnetometers located at high polar cap latitudes and negative H deviations at low polar cap latitudes when $B_y < 0$ and opposite signatures when $B_y > 0$. The signs of these predictions are in agreement with ground magnetometer observations [*Svalgaard*, 1968, 1973; *Mansurov*, 1969; *Berthelier and Guerin*, 1972; *Wilcox*, 1972], and the observed maximum in these effects at or near local noon is consistent with equipotential contours when the local time variation of the ionospheric Hall conductivity is taken into account. Ground magnetometer responses to ionospheric electric fields depend in complex ways on ionospheric conductivities, parallel currents, current closure paths, and other effects. For this reason it is not considered worthwhile to attempt more detailed correlations between the electric potential contours and ground magnetometer data than those discussed above to show the consistency of the electric field and ground magnetometer data.

The above polar cap electric field dependencies on B_y may be understood in terms of a model in which the line of reconnection of the interplanetary and terrestrial magnetic fields is inclined at an angle that depends on the direction of the interplanetary field (W. D. Gonzalez and F. S. Mozer, unpublished manuscript, 1973). In this model, the reconnection line coincides with the ecliptic plane when the interplanetary field is purely southward, whereas for pure positive or negative y-directed interplanetary fields the reconnection line, LL', is tilted as indicated in Figure 13. The interplanetary field reconnects with the geomagnetic field only along the line LL', because the postreconnection flow of plasma and magnetic field along the magnetopause prevents interplanetary field lines from reaching the magnetopause elsewhere. Since the immediate postreconnection flow of plasma and magnetic field is perpendicular to the reconnection line, there is a tendency for the polar cap flow to occur predominately over the morning side of the northern hemisphere when $B_y > 0$ and over the afternoon side when $B_y < 0$. Thus reconnection of the y component of the interplanetary magnetic field in the above model causes rotation of the two-cell convection pattern around the sun-earth line that shifts the flow pattern toward dawn (dusk) in the northern hemisphere and toward dusk (dawn) in the southern hemisphere when $B_y > 0$ ($B_y < 0$), in agreement with the experimental data.

Three-Dimensional Problem

From the discussion and observational evidence presented, it can be concluded that both the north-south and azimuthal components of the interplanetary magnetic field are involved in the interaction with the geomagnetic field.

Preliminary evidence of this three-dimensional interaction is presented in Figures 10 and 12, in which the heavy lines indicate the data collected when the southward component of the interplanetary magnetic field was the largest that was observed in the body of data at that local time. In all cases, the maximum effect expected for the given direction of the azimuthal component occurred when the southward component was largest.

Magnetospheric Parameters Deduced from the Average Polar Cap Electric Field

The length of the magnetospheric tail can be estimated from the average dawn to dusk electric field by requiring that the ionospheric end of a magnetic field line flow across the polar cap in the same time that the interplanetary end of the same field line travels the length of the tail at the solar wind velocity [*Dungey*, 1965]. Assuming a solar wind speed of 400 km/sec and a 32° wide polar cap, the

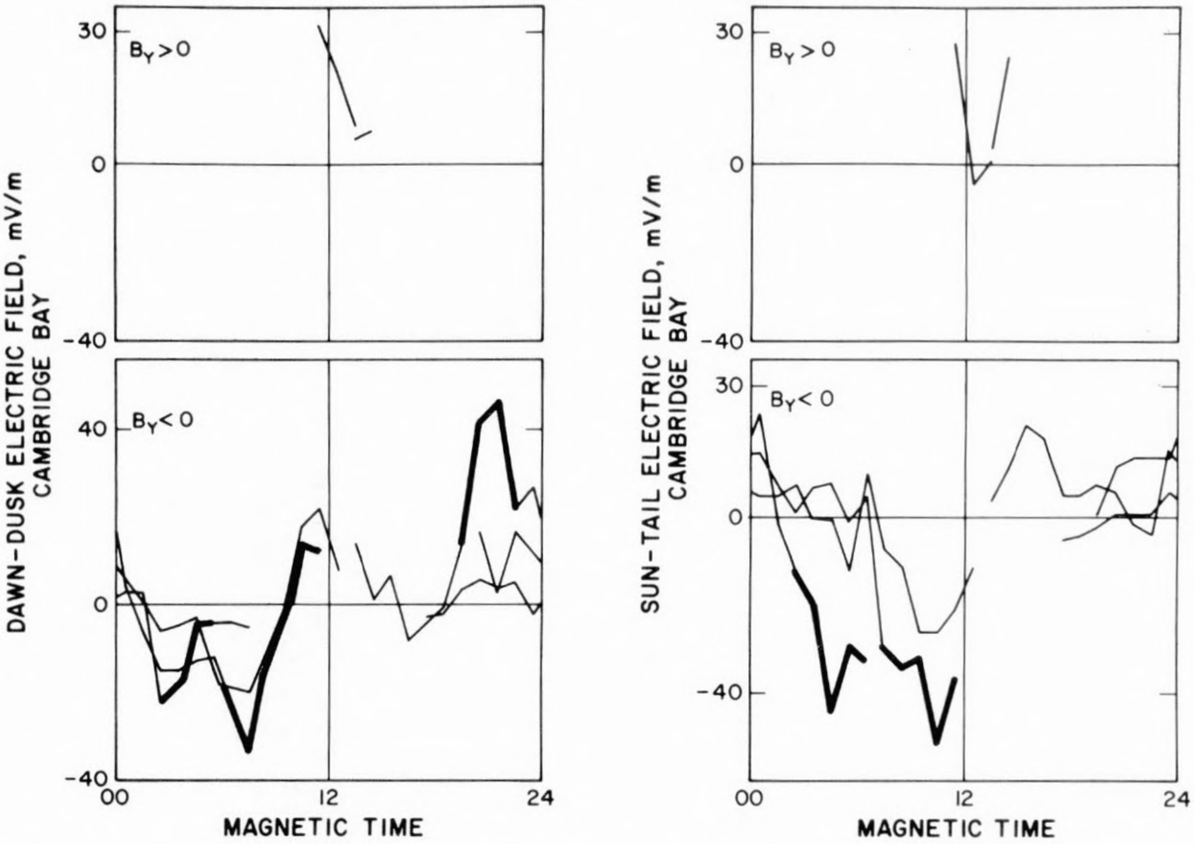

Fig. 12. Hourly averages of the electric field components measured at Cambridge Bay in a nonrotating frame of reference for $B_y > 0$ and $B_y < 0$.

length of the tail is computed from the average electric field strength to be 670 R_E. This estimate is an upper limit to the actual tail size (defined as the distance to the nightside neutral point or line) because the interplanetary end of the magnetic field line of interest will have flowed past the neutral point or line when the reconnection takes place. It is interesting to compare the above upper limit for the length of the tail with a lower limit of 320 ± 90 R_E obtained from studies of solar particle penetration into the polar cap [*Stone and Evans*, 1971]. Thus the typical length of the tail is estimated from these two measurements to be between 300 and 700 R_E. These estimates are consistent with direct satellite observations [*Ness et al.*, 1967; *Fairfield*, 1968; *Mariani and Ness*, 1969]. It is also important to note that the tail geometry or polar cap boundary is expected to fluctuate greatly owing to fluctua-

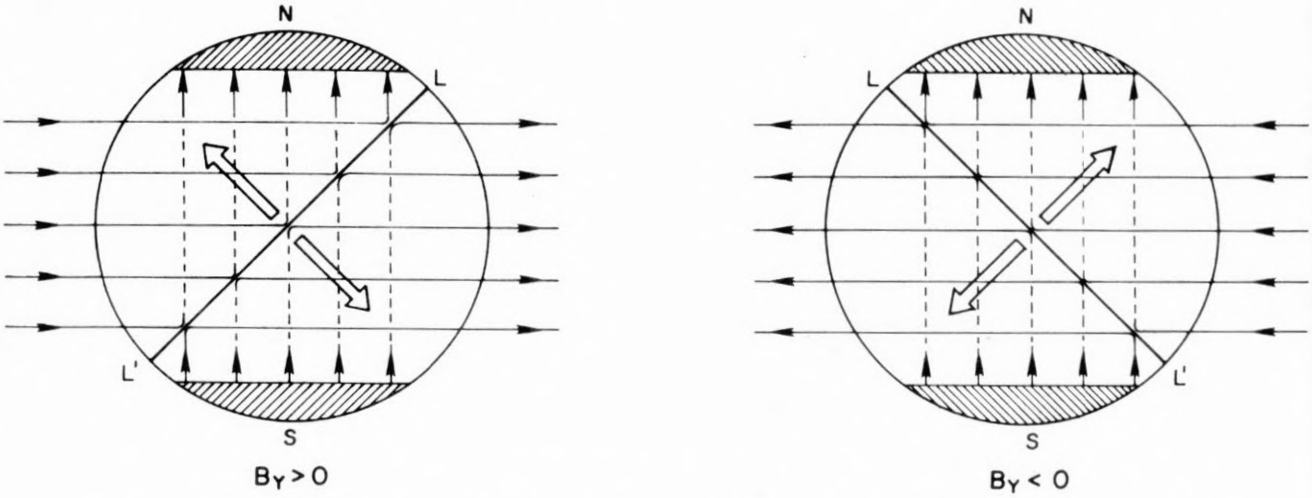

Fig. 13. View from the sun of the magnetopause convection due to the assumed reconnection between an azimuthal interplanetary magnetic field and the geomagnetic field for the cases of $B_y > 0$ and $B_y < 0$. The solid lines are interplanetary magnetic field lines, the dashed lines are terrestrial magnetic field lines on the magnetopause, line LL' is the reconnection line, the hatched areas are the polar caps, and the white arrows indicate the direction of the postreconnection flows.

tions in the electric field like those illustrated in Figures 1 and 2.

The energy input into the tail can be estimated from knowledge of the polar cap potential φ and the length of the tail L by integrating the Poynting flux flowing toward the neutral sheet over the area of the tail. Thus

$$W = (c/2\pi)\varphi B_T L \tag{1}$$

where W is the energy flowing into the tail per second and B_T is the average magnetic field strength in the tail. For $L = 500\ R_E$, $\varphi = 55$ kV, and $B_T = 20\ \gamma$, the energy inflow is about 5×10^{19} ergs/sec, which is sufficient to power all known magnetospheric processes.

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