Two Substorm Studies of Relations between Westward Electric Fields in the Outer Plasmasphere, Auroral Activity, and Geomagnetic Perturbations

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In two case studies of magnetospheric substorms, temporal variations of the westward component of the magnetospheric convection electric field in the outer plasmasphere were compared with auroral activity near $L = 7$ and with variations in the geomagnetic field at middle and high latitudes. The substorms occurred on July 29, 1965, near 0530 UT and on August 20, 1965, near 0730 UT. The results on the westward electric field E_w were obtained by the whistler method with data from Eights, Antarctica ($L \sim 4$). All-sky camera records were obtained from Byrd, Antarctica ($L \sim 7$), located within about 1 hour of Eights in magnetic local time. It was found that E_w within the outer plasmasphere increased rapidly to substorm levels of ~0.5 mv/m about the time of auroral expansion at nearby longitudes. This behavior differs from results obtained from electrostatic probes on balloons, which show E_w reaching enhanced levels before the expansion. A close temporal relation was found between the rapid substorm-associated increases in E_w and a well-known type of nightside geomagnetic perturbation. Particularly well defined was the correlation of E_w rise with a large deviation of the D component at middle latitudes.

Much has recently been learned about magnetospheric convection electric fields [e.g., *Maynard*, 1971; *Mozer*, 1971; *Heppner*, 1971; *Haerendel*, 1972; *Cauffman and Gurnett*, 1971], and it is now possible to make detailed comparisons between these fields and certain related phenomena. In a recent presentation of several case studies, preliminary comparisons were made between magnetospheric E-W electric fields deduced from whistlers, the interplanetary magnetic field orientation, and substorm bay events [*Carpenter et al.*, 1972]. The present report extends these comparisons and shows relations among the electric fields previously reported, auroral activity, and midlatitude and high-latitude magnetic perturbations. The case studies indicate that the 'growth phase' signature of the westward electric field E_w observed within the plasmasphere may differ appreciably from the signature believed to exist at greater distances. This report also reveals a close temporal relation between a rapid substorm-associated rise in the E_w in the plasmasphere and a well-known type of nightside geomagnetic perturbation.

SOURCES OF DATA

The data include records from magnetic observatories in the United States, Canada, Iceland, and Antarctica, all-sky camera records from Byrd, Antarctica, and VLF convection electric-field data from Eights, Antarctica. Figure 1 shows the distribution of stations in invariant latitude and magnetic local time at ~0600 UT, when Eights and Byrd are near local midnight. For illustration the solar direction is taken as upward, and the solar magnetospheric Z axis as out of the paper. A 600-km-radius circle represents the field of view of the Byrd all-sky camera. The approximate 'viewing' area of the Eights whistler station ($L \sim 4$) (dashed curve) is estimated from statistics on the latitudinal extent of observed multicomponent whistlers and from comparison of simultaneous whistler recordings at Byrd and Eights, which are separated by about 1 hour in magnetic local time. The E-W component of the electric field at various equatorial points that map into this area was determined from observations of cross-L drifts of multiple whistler paths. (In the present application of the whistler method, only information on the path L value is obtained; the path longitudinal position within the viewing area is not known. For further information on the method see the paper by *Carpenter et al.* [1972].)

The midlatitude magnetic observatories range westward from Agincourt and Fredericksburg (near the meridians of Eights and Byrd) to Victoria, Canada. The higher-latitude group ranges from Leirvogur (about 3 hours east of Eights) to College, Alaska (about 6 hours to the west).

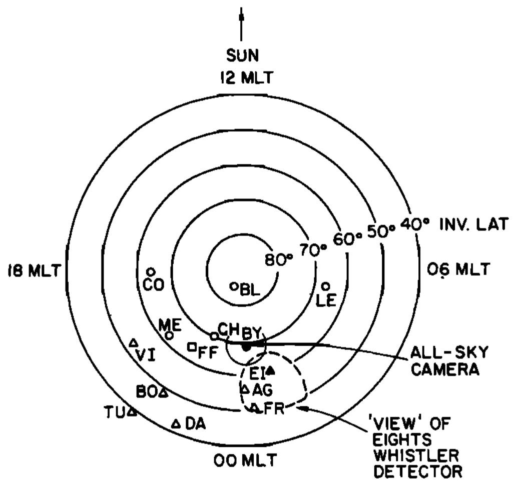

Fig. 1. Distribution in invariant latitude and magnetic local time of ground stations providing data used in this report. The distribution is illustrated for ~0600 UT, when the two southern-hemisphere stations, Eights (EI) (solid triangle) and Byrd (BY) (solid circle), Antarctica, are near local midnight. The solid curve (with a radius of 600 km centered at BY) represents the field of view of the Byrd all-sky camera. The dashed curve shows the approximate 'viewing' area of the EI whistler station ($L \sim 4$). Open circles represent the high-latitude magnetic observatories: Leirvogur (LE), Churchill (CH), Baker Lake (BL), Meanook (ME), and College (CO). Open triangles represent the midlatitude magnetic observatories: Fredericksburg (FR), Agincourt (AG), Dallas (DA), Boulder (BO), Tucson (TU), and Victoria (VI). The square represents an observatory at Flin Flon (FF), where an impulsive precipitation event (balloon X rays) was observed at 0640 UT.

Case Study of July 29, 1965

Figure 2 compares E_w variations on July 29, 1965, with variations of the interplanetary magnetic field and of the surface geomagnetic field. Figure 3 shows corresponding all-sky camera data.

The period of Figure 2 is centered roughly 36 hours following the beginning of a weak magnetic storm and during a period of regular but relatively well separated surges of substorm activity. Sums of Kp on July 26, 27, 28, and 29 were 7, 16, 23, and 20, respectively. Hourly Dst for 0500–0600 UT on July 29 was $-6\ \gamma$.

Relation of E_w and D. A prominent feature of Figure 2 is the approximate time coincidence of the large surge of E_w at ~0520–0620 UT and perturbations in nearly all the magnetic traces. One of the best-defined magnetic effects occurs in the D component variations (Figure 2, bottom). These begin at about the time of the rapid increase in E_w at 0520–0530 UT and appear to be typical substorm-associated D events [*Akasofu and Meng*, 1969; *Meng and Akasofu*, 1969]. At Victoria the deflection in D was eastward. Tucson and Boulder appear to have been in a transition region, whereas at Dallas and further east the deflection was westward. The D events near the meridian of Eights (Fredericksburg and Agincourt) showed maximum westward deflection near the time of peak E fields and decayed as E_w dropped to 0. The E field then reversed to be relatively large and eastward, but there was no similar change in D. The relation between E_w and the Fredericksburg D component is shown on an expanded time scale in the middle and lower parts of Figure 4.

Relation of E_w and auroral activation. In the period of rapid increase in E_w at 0520–0530 UT, Byrd all-sky photographs (Figure 3, sixth row) showed an enhancement of auroral activity near the NE horizon (upper right in the photographs), which is the equatorward boundary of the auroral oval near the midnight meridian. Auroral activity then spread rapidly toward the morning sky, a typical morning feature of an auroral substorm. The auroras were most active in the period 0540–0600 UT, when both the electric field and the negative bay at Byrd were near their peak intensities.

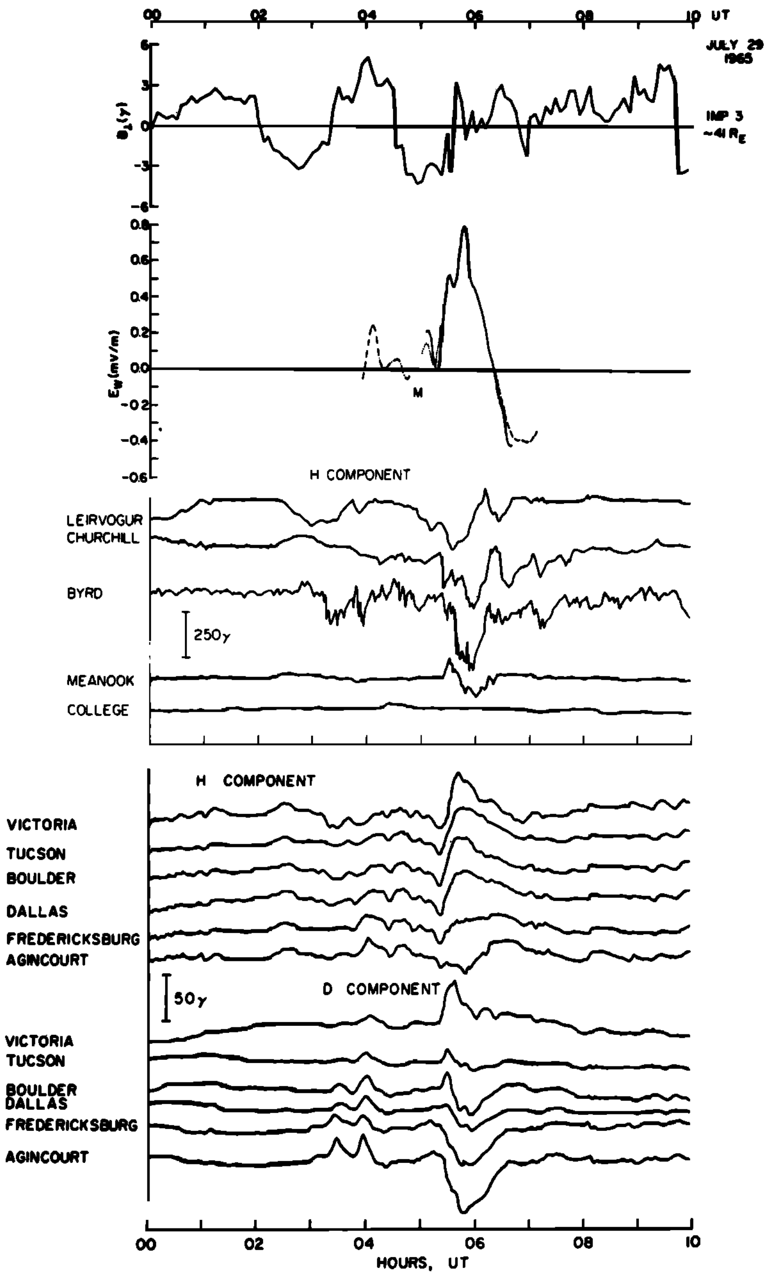

Fig. 2. Comparison of E_w in the magnetosphere and various magnetic records during a July 29, 1965, period of substorm activity. The top panel shows Imp 3 5.46-min averages of the interplanetary magnetic field component perpendicular to the dipole equator (transformation from solar-ecliptic coordinates courtesy of C. Meng). Imp 3 was at ~41 R_E at a SEP angle of 296°, corresponding to the ~1600 local time meridian. The second panel shows details of E_w variations in the outer plasmasphere at $4 \lesssim L \lesssim 4.5$ determined from individual whistler paths observed at Eights, Antarctica. Interruptions and terminations of curves are due to corresponding changes in measurable properties of the whistlers. The M near the time scale identifies magnetic midnight at the whistler station. The third panel shows H component magnetic traces from the high-latitude observatories, and the bottom panel shows the H and D component signatures from the midlatitude observatories.

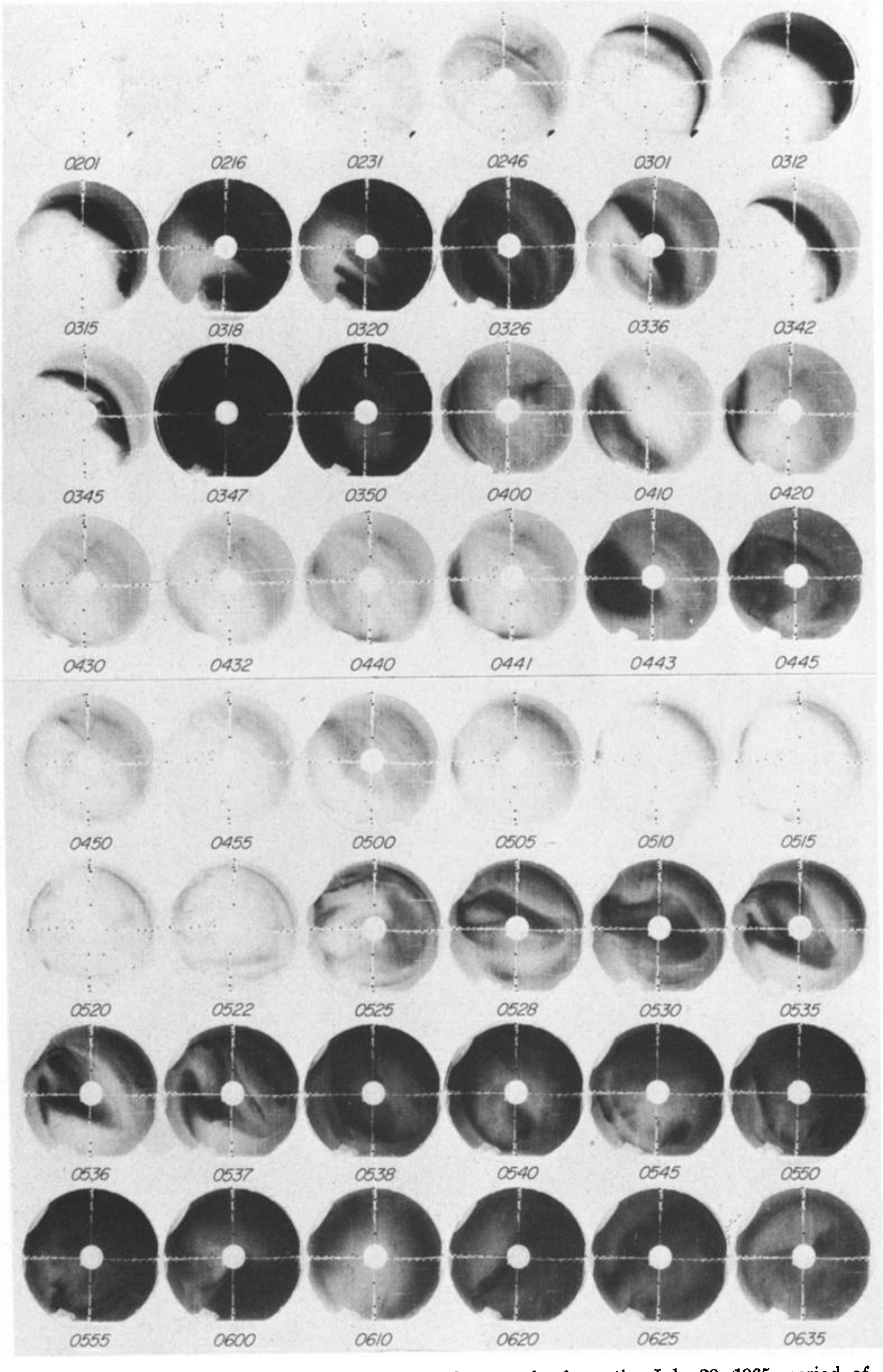

Fig. 3. Selected Byrd, Antarctica, all-sky photographs from the July 29, 1965, period of Figure 2. Magnetic north (equatorward) is to the upper right in the photographs; magnetic west is to the upper left.

The electric field reversed its sign to become eastward at ~0620 UT. This reversal coincided approximately with a reversal of auroral motions. Between 0600 and 0617 UT, auroras were drifting eastward. At about 0618 UT a bright band appeared near the zenith of Byrd and

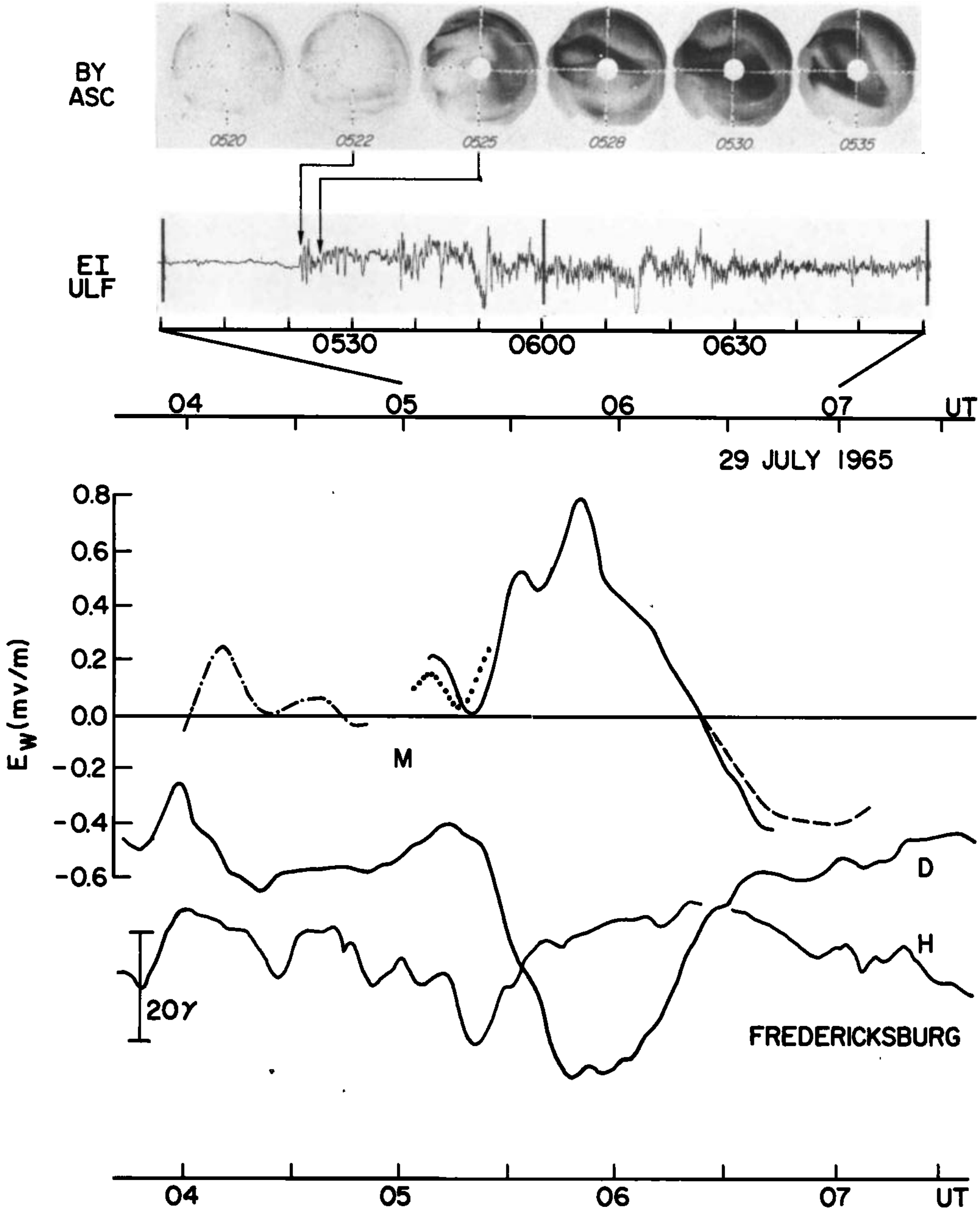

Fig. 4. Expanded time scale presentation of the correlated event of July 29, 1965. The top panel shows a set of Byrd, Antarctica, all-sky photos from Figure 3, repeated for detailed comparison with the micropulsation record from Eights, Antarctica, in the second panel. The third panel shows the electric-field signature presented in the second panel of Figure 2. The bottom panel shows the *H* and *D* components from the Fredericksburg magnetometer, near the meridian of the whistler observations.

moved rapidly westward (see the photographs taken at 0620 and 0625 UT). It is not clear how the reversal in cross-L plasmaspheric drifts from inward to outward is related to this auroral reversal from eastward to westward. There was no clear poleward or equatorward motion of auroras in the period immediately following 0650 UT.

Interplanetary magnetic field. The relation of the interplanetary magnetic field and E_w for this case was discussed briefly by *Carpenter et al.* [1972]. In Figure 2 (top) the comparison is changed slightly so as to present the interplanetary data in terms of $B_\perp$, the component normal to the earth's dipole equator. As was noted in the earlier paper, there appears to be a relationship between negative increases in $B_\perp$ at ~0200, 0430, and 0650 UT and a sequence of bays shown, for example, by the Byrd magnetometer. The relationship is similar to the type recently discussed by *Foster et al.* [1971], *Nishida* [1971], *Arnoldy* [1971], and *Rostoker et al.* [1972], among others. The largest bay event, near 0530 UT, follows a negative increase in $B_\perp$ of about 7 γ near 0430 UT. The negative excursion of the interplanetary field was relatively brief; it decayed after about 1 hour as the more intense part of the E_w event developed.

Growth phase. The brevity of both the interplanetary event and the following substorm complicates identification of a growth phase in the E_w data. The increase in E_w near 0500–0510 UT occurred near the time of a slight increase in the brightness of the auroras (Figure 3, sixth row). At Leirvogur there was a beginning of a negative bay at 0455 UT (Figure 2), and abrupt beginnings occurred at Churchill and Byrd at 0520 and 0525 UT, respectively. At ~0525 UT, when nearby auroral and bay activation occurred, E_w rose rapidly from low levels and clearly had not already 'grown' to a relatively large increasing level at this time.

The correlated nature of the rapid increase in E_w and other effects is emphasized in Figure 4. The Byrd all-sky films (samples of which appear in the top panel) reveal that auroral activation occurred on the NE horizon (in the general direction of Eights) at 0523 ± 1 min. An uncalibrated micropulsation record from Eights (second panel) shows the onset of a Pi 2 event at ~0522 ± 20 sec. In a recent review *Rostoker* [1972] noted the value of Pi 2 bursts as indicators of substorm onsets.

The onset times of the auroral activation and Pi burst fall well within the interval 0525 ± 5 min, which is our present estimate of the beginning of the rise in E_w near $L = 4$ (third panel). Improved resolution of the E_w variations is expected as the whistler technique is further developed.

CASE STUDY OF AUGUST 20, 1965

Figure 5 repeats for August 20, 1965, the format used in Figure 2, and Figure 6 presents examples of corresponding Byrd all-sky camera films. In the August event, as in the July 29 event, a weak magnetic storm was underway, but the August event was preceded by activity of somewhat greater intensity and longer duration. Sums of Kp on August 17, 18, 19, and 20 were 19, 19, 30, and 24, respectively. Minimum hourly Dst during the interval of Figure 5 was −10 γ at 1000–1100 UT.

Activity on August 20, 1965, was previously described by *Coroniti et al.* [1968], who noted the occurrence of several large substorms in close succession between ~0700 and 1300 UT. The prolonged nature of the activity is reflected in the E_w curves of Figure 5, which do not exhibit a reversal after the large westward increase but instead remain westward until near local dawn (~1100 UT).

Relation of E_w and D. In Figure 5, as in Figure 2, there is a correlated event in the E_w curves and many of the magnetic signatures. The D variations resemble those of Figure 2 in several respects, exhibiting a large deflection at ~0730 UT, when the westward field began its main substorm increase. The August 20 D event appears to recover slowly in comparison with the 'isolated' event of July 29, the slow recovery probably reflecting the prolonged nature of the associated substorm activity.

Relations of E_w, auroras, the interplanetary magnetic field $B_\perp$, and bay activity. The interplanetary magnetic field component normal to the dipole equator began a brief negative excursion near 0410 UT, reached a maximum negative value of ~−4 γ at ~0455 UT, and then quickly reversed to positive values at ~0505 UT. Shortly after 0500 UT there was a small bay event at Byrd, accompanied by a westward surge (see the all-sky photographs for 0510–

0515 UT in Figure 6). No clearly related changes in E_w were detected in the observed whistler paths at $L \sim 3.7$.

Near 0550 UT, $B_\perp$ turned sharply downward and began an initially irregular but enduring negative trend. At ~0620 UT, E_w in the outer

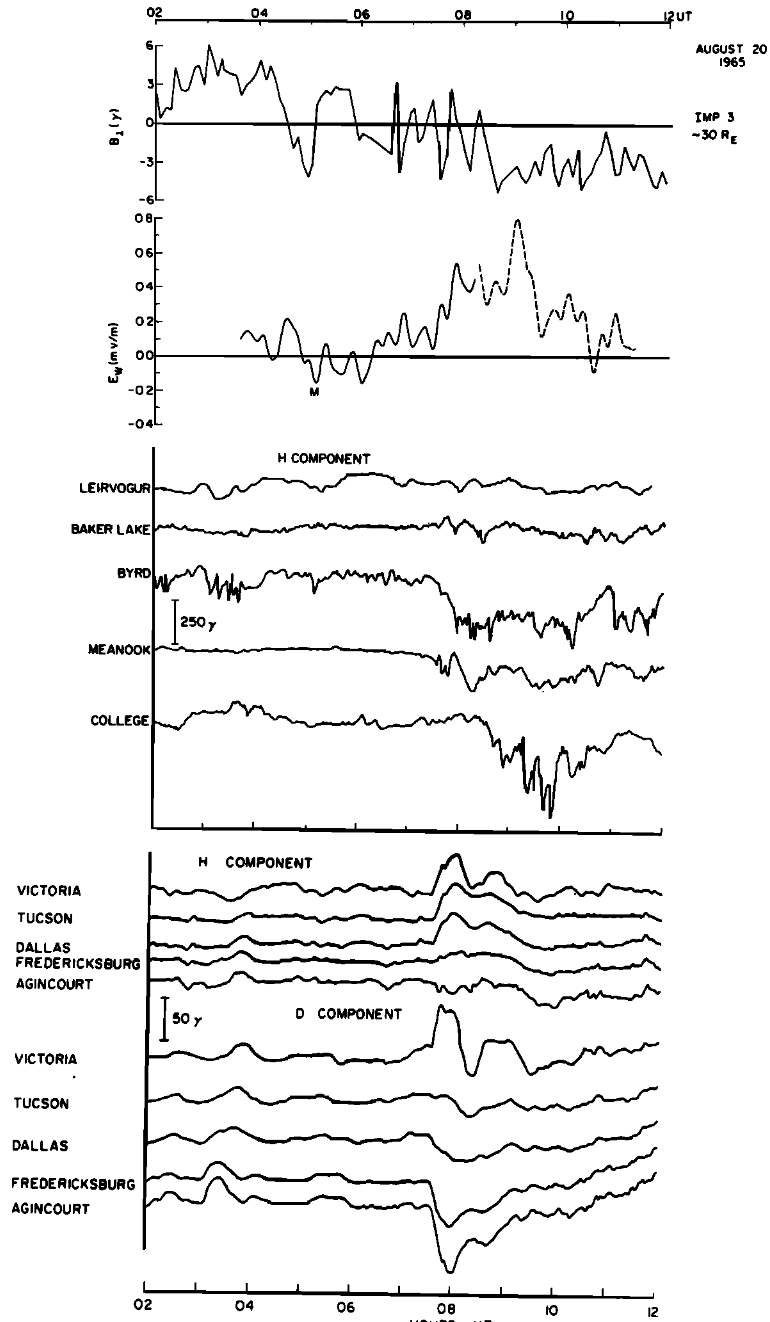

Fig. 5. Comparison of E_w in the magnetosphere and various magnetic records during an August 20, 1965, period of substorm activity. The format is essentially the one used in Figure 2. Imp 3 was at ~30 R_E at a SEP angle of 324°, corresponding to the ~1400 local time meridian.

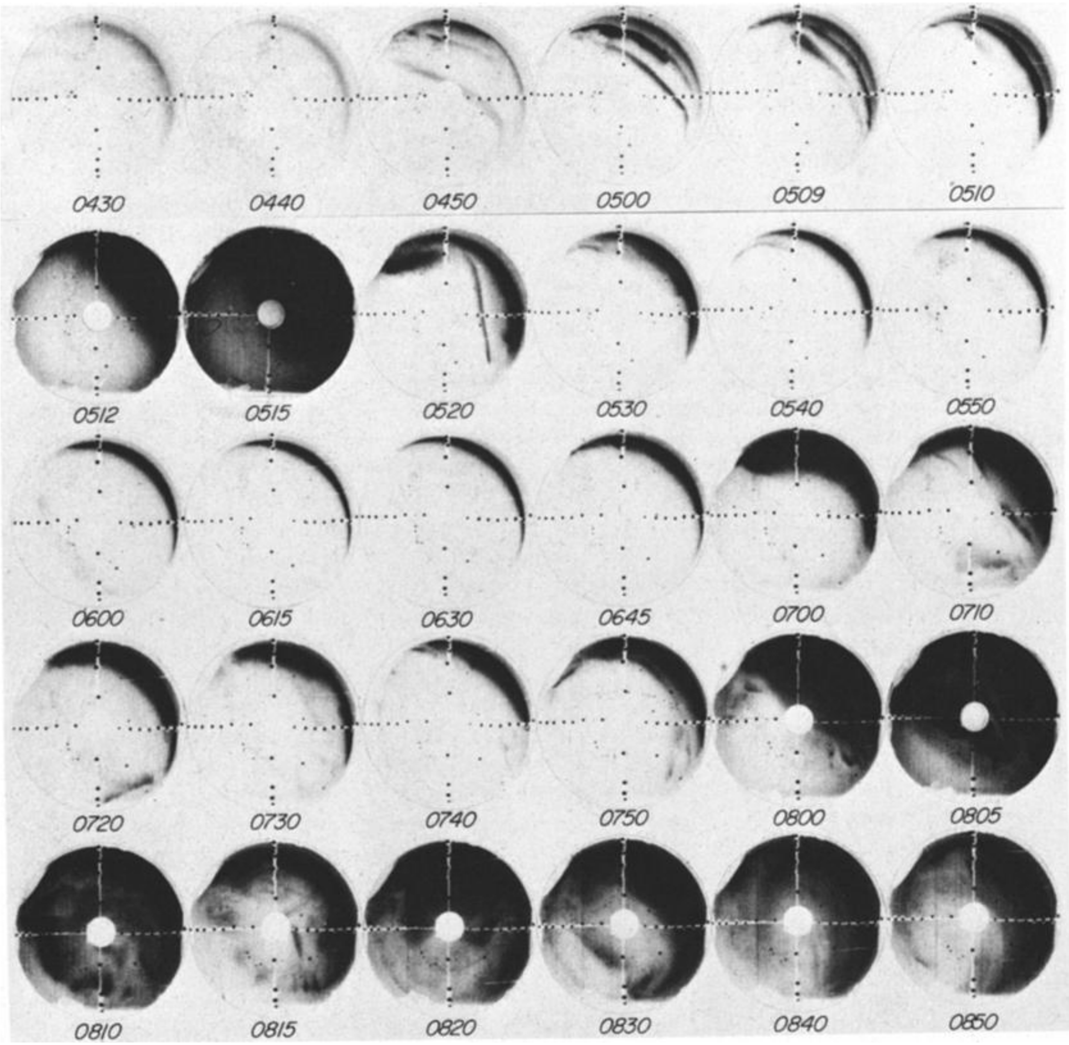

Fig. 6. Selected Byrd, Antarctica, all-sky camera photographs from the August 20, 1965, period of Figure 5. Magnetic north (equatorward) is to the upper right in the photographs; magnetic west to the upper left.

plasmasphere ($L \sim 3.7$) turned positive and began to fluctuate near ~0.15 mv/m. Examination of the Byrd all-sky photographs revealed an enhancement of the brightness of auroras near the equatorward horizon at 0638 UT. The auroras were active but too distant for detailed examination of motions. At Flin Flon, Canada, an impulsive precipitation event (balloon X rays) was observed at 0640 UT [*Coroniti et al.*, 1968].

At ~0730 UT there was an increase in E_w as a negative bay began at Byrd. *Coroniti et al.* [1968] reported a large impulsive electron precipitation event at Flin Flon at 0735 and concluded from Flin Flon and College magnetograms that a substorm expansion phase began at this time. At about 0750 UT there was a further increase in E_w as auroras observed from Byrd (Figure 6) began to spread poleward, first rather slowly and at 0755 UT more rapidly. Active displays continued until twilight (~1400 UT).

CONCLUDING REMARKS

In two substorm studies a large (factor of ~5) surging increase in E_w in the outer plasmasphere at $L \sim 4$ was found to be closely correlated in time with an enhancement of auroral activity observed from Byrd, Antarctica ($L \sim 7$). The auroral and E_w observations were coincident in longitude within about 15°. Before the large E_w increase and auroral activation there was activity in E_w at lower levels near 0.1–0.2 mv/m. This activity appeared to be correlated with one or more of the following: distant auroral activity, small local fluctuations in auroras, X-ray precipitation events, and minor magnetic disturbances. It is not clear yet in what sense this initial activity in E_w may be classified as a growth phase effect.

The foregoing description of E_w variations differs from the electric-field signatures found from balloon-borne detectors by *Mozer* [1971], who reported a growing westward field that reaches a high level before the time of magnetic bay onset in the vicinity of the observing balloon. The lack of agreement may be due in part to the great variety and complexity of substorms and to the attendant difficulties in identifying (and in obtaining agreement on) the various stages of substorm development. That the differences are partly real is suggested by four other whistler case studies of substorms (given below), for which all-sky camera data were not available, that showed relations similar to those described above between E_w increases and mid-latitude D component events. We are indebted to one of the referees (F.S.M.) for the suggestion that some of the differences between the balloon and the whistler results may be due to the increase of the equatorial magnetic field at the time of substorm expansion. The associated induced electric field might be detected near the magnetic equator by the whistler method but not near the ionosphere by balloons. This problem is currently being studied by Lars Block and one of the authors (D.L.C.); preliminary results (in preparation) suggest that $\partial \mathbf{B}/\partial t$ effects are indeed important but are not capable of explaining more than a part of the rapid increase in E_w reported here. Explanation of the difference between balloon and VLF results thus remains a problem for further experimental and theoretical research.

The second main point of interest in the two case studies is the occurrence at middle latitudes of a large deviation of the D component of the geomagnetic field at about the onset time of the main surge of E_w. (Similar events have been observed in case studies on July 15, July 25, and October 13, 1965, and June 29, 1967.) The deviation was westward in the longitude range of the convection electric-field observations. At present it is not clear how the E_w increase and the D event are related. In dipole geometry a westward electric field in the magnetosphere of 0.5 mv/m at $L = 4$ will map into the ionosphere with an intensity of 4 mv/m [*Mozer*, 1970]. If the Hall conductivity is sufficiently high, this field might cause an appreciable westward deflection of the geomagnetic field. However, the D component does not exhibit a pronounced reversal at the time of the reversal in E_w in the magnetosphere. Furthermore, large substorm-associated increases in E_w within the plasmasphere are frequently localized in longitude and in particular do not usually extend well into the premidnight sector [e.g., *Park and Carpenter*, 1970]. In contrast, the D (and H) events are evidently spread widely in longitude (Figures 2 and 5) and may reflect a large-scale pattern of field-aligned currents. Indeed, the longitudinal variations of the D component (from Victoria to Agincourt) are in good agreement with the pattern discussed by *Akasofu and Meng* [1969] and *Meng and Akasofu* [1969]. We tentatively conclude that E_w within the plasmasphere surged rapidly when the field-aligned current system began to grow. Improved knowledge of these relationships should result from expected future improvements in resolution of the onset time of E field events.

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