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# NEW WHISTLER EVIDENCE OF A DYNAMO ORIGIN OF ELECTRIC FIELDS IN THE QUIET PLASMASPHERE

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Abstract. A comparison of whistler data from four consecutive magnetically quiet days July 4-7, 1973, confirms and extends previous whistler results on quiet day cross-L drift motions in the outer plasmasphere near L = 4. A pattern of morningside outward and afternoonside inward drifts at ≈200 m/s ($|E_W| \approx 0.1$ mV/m) was repeated daily. ($E_W$ is the westward component of the magnetospheric electric field at the equator.) Over the four days the onset of the outward drift activity shifted backward in time from ≈1000 MLT to ≈0500 MLT. There was a corresponding shift in the harmonic series representing $E_W$. On the first day the largest term was semidiurnal; on the fourth day it was diurnal. The data provided an opportunity to investigate in some detail the cross-L drift velocity at spaced L values. During seven periods of the order of 1-hour duration, drifts of the order of 200 m/s could be simultaneously measured at points spaced over approximately 1 $R_E$ in equatorial radius. The inferred equatorial east-west electric fields near L = 4 decreased at least as rapidly as $L^{-3/2}$ with increasing distance. (In a dipole field an equatorial variation as $L^{-3/2}$ would be expected if an east-west field that is constant with latitude were present at ionospheric heights.) There is some indication that the faster drop-offs, with variation roughly as $L^{-4}$, occurred during the first two days of quieting following disturbance and that the falloff approached $L^{-3/2}$ on the third and fourth days. It is speculated that day-to-day changes in subauroral ionospheric conductivity during the quiet period may have been responsible for the 'shielding' of the field from high latitudes. The data strongly support the concept that the observed electric fields originate at middle to low latitudes, apparently in an ionospheric dynamo process. The noon-midnight asymmetry (or noon bulge) of the plasmasphere reported from spacecraft appears to be a consequence of the quiet day flow pattern.

## 1. Introduction

In the study of magnetospheric electric fields and the associated plasmaflow activity it is important to develop a quiet day reference or base line. Such a reference is now taking shape; it appears to be dominated by fields or flows that originate in an ionospheric dynamo process. The ionospheric dynamo involves motion of conducting ionospheric layers across geomagnetic field lines, the motions or tidal winds being the result of pressure gradients induced by solar heating and lunar gravitational effects. In this dynamo process, electrostatic fields are expected to develop and to be mapped upward along field lines to the underlying magnetosphere [e.g., H. Maeda, 1964, 1970; K. Maeda and Kato, 1966; Matsushita, 1971]. However, experimental investigation of such fields has depended upon the development of suitable probing techniques and the identification of the large middle and high-latitude electric fields that are of solar-magnetospheric origin. Improved methods for the measurements now exist; incoherent scatter radars have revealed repeatable patterns of quiet day drift activity at E and F region heights [e.g., Evans, 1972; Blanc et al., 1977]. Evidence that dayside drifts observed at L ≈ 3.2 originate in a dynamo process was presented by Evans [1972]. In a 1973 review of data on plasmaspheric electric fields, Mozer [1973] concluded that electric fields near L = 3 are predominantly of dynamo origin. Richmond et al. [1976] have concluded that ionospheric winds can explain observed quiet time middle and low-latitude electrostatic fields. Recently, however, workers at the Saint-Santin radar facility at L = 1.8 [Blanc et al., 1977] compared their results with data from Millstone Hill and Arecibo and concluded that the question of the origin of the observed quiet day fields remains open.

Whistler measurements of the cross-L motions of magnetospheric field-aligned propagation paths or ducts in the outer plasmasphere also revealed generally repeatable quiet time drift patterns [Carpenter and Seely, 1976]. The patterns were found to be in rough agreement with the dayside radar data acquired at Millstone Hill near the longitude of the observing whistler stations [Evans, 1972]. Clear differences were noted between the quiet time patterns and results from whistlers on substorm-associated drifts in the outer plasmasphere; from this and other evidence the quiet time drifts were tentatively attributed to a dynamo process. Richmond [1976] fitted an electrostatic potential function to radar and whistler observations and noted that when mapped to the magnetospheric equator, the resulting convection pattern differs from the patterns expected from solar wind magnetosphere interactions.

The present note provides new information pertinent to the origin of quiet day drifts in the plasmasphere and to the noontime plasmaspheric bulge that appears to develop as a result of the drifts. A whistler path drift analysis of four successive 24-hour periods of magnetic quiet was performed. The results confirm earlier findings and extend them by showing new evidence of a decrease with increasing equatorial distance in the east-west magnetospheric electric field at L ≈ 4. The results also provide additional evidence of a secondary maximum in plasmapause radius near noon, apparently the phenomenon reported by Gringauz and Bezrukikh [1976].

## 2. Experimental Data and Methods

The whistler data were recorded in 1973 on a synoptic 1-every-5-min basis at Siple, Antarctica (76°S, 84°W, L ≈ 4.2). This sampling scheme

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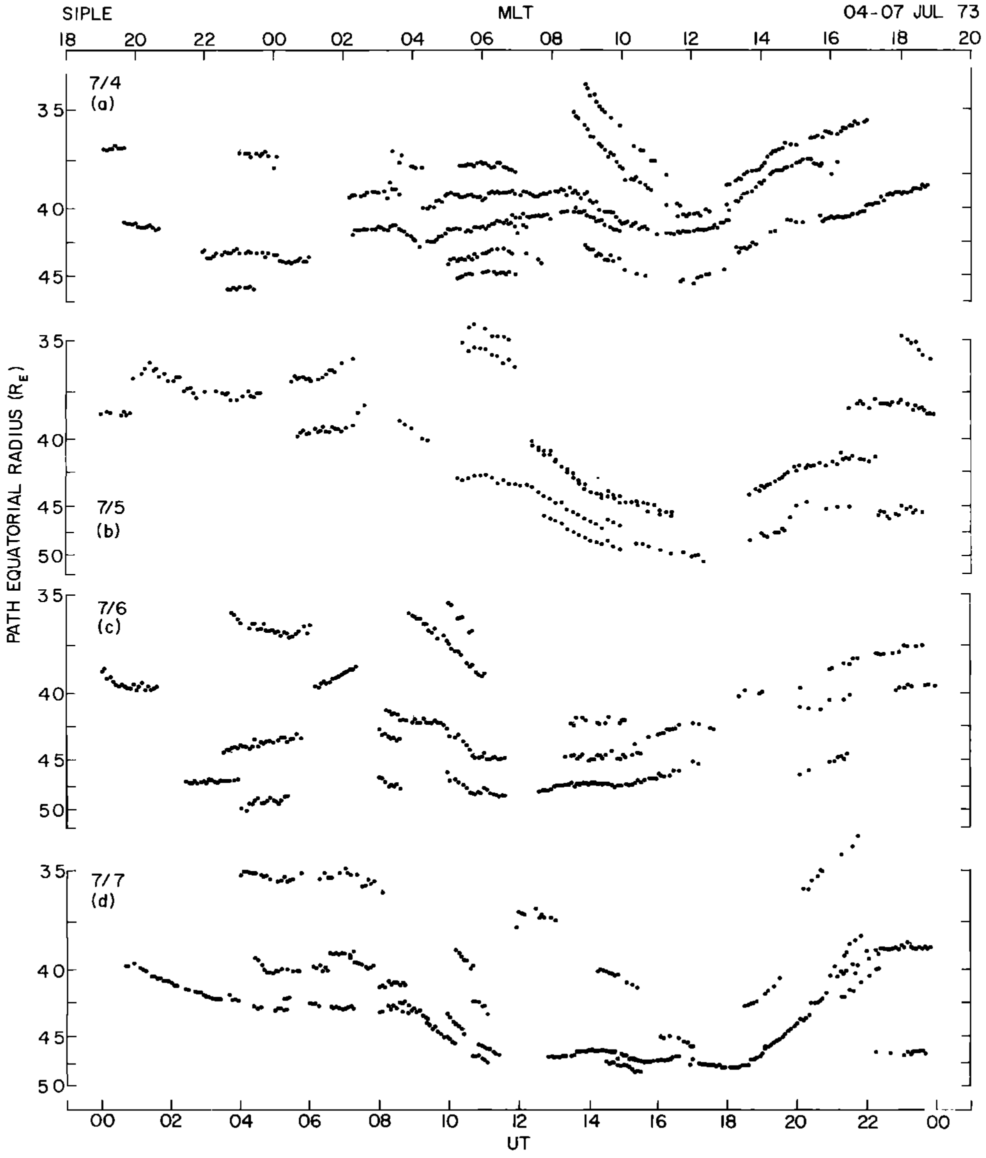

Fig. 1. Whistler path equatorial radii variations on four successive magnetically quiet days. The whistlers were recorded at Siple, Antarctica, July 4-7, 1973. Path equatorial radius (values increasing downward) is plotted versus UT (below) and MLT (above) (see text for additional details).

keeps magnetic tape usage and analysis costs within manageable limits, while approaching the ideal of continuous recording. In the analysis, 35-mm spectrographic films of well-defined whistler events received in successive runs were compared by overlay techniques. Individual whistler components which were present for periods of 30 min or more were then scaled for path equatorial radius. This was done through measurement of the whistler nose frequency, which is approximately proportional to the equatorial electron gyrofrequency (for discussions of whistler diagnostics, see Park [1972], Brice and Smith [1971], or Corcuff [1975]). In determining continuity of a whistler component, attention was paid to its dispersion properties, to the relation of the component to other components, and to the relation of the component to the causative atmospheric. During the austral winter, causative atmospherics can usually be directly identified on the Siple records for about 12 hours of the day. Continuity is not easily determined. Rapid changes in the fine structure of whistlers may occur, and the pattern recognition work may be complicated by the presence of two or more 'families' of whistlers, centered at different longitudes within the station's ±≈20° longitudinal 'view." For further discussion of the analysis methods used, see Carpenter and Seely [1976].

Information on cross-L drift activity was obtained by differentiation with time of the data on whistler path equatorial radius. Data from several paths spaced in latitude (and longitude) are often available. This opens the possibility, explored briefly in this paper, of investigating variations with equatorial radius in the magnetospheric east-west electric field.

## 3. Experimental Results

In a previous paper, two cases of 24 hours of observations were described [Carpenter and Seely, 1976]. Both cases represented magnetically quiet days preceded by three other quiet days. In conjunction with shorter data sets these data were found to show a generally repeatable cross-L convection pattern. The most distinctive case-to-case variation within the general pattern was in the time of occurrence, or phase, of a dawnside outward drift.

In order to confirm and extend these results a study was made of four successive quiet days, July 4-7, 1973 (data from July 7 were shown in the previous paper and were rescaled for this study). Values of $\Sigma K_p$ for the days July 4-7 were 9, 7, 6, and 5. Figure 1 presents a plot of whistler path equatorial radius versus time on the four days (UT below, MLT above). Most of the available data are shown; those omitted (generally to avoid crowding) tend to follow the trends indicated. Although there is variation in detail from day to day, the previously reported features of prenoon outward and postnoon inward drift are clearly present.

The scale of path equatorial radius in Figure 1 is linear in $R_E^{-2}$. Time variations in this quantity contain an $R_E^{-3}$ factor which cancels the $R_E^3$ dependence of $B^{-1}$ in the simplified hydromagnetic relation $v_r = -E_w/B$ ($v_r$ is the radial bulk flow velocity at the equator, and $E_w$ is the westward component of the equatorial electric field). This simplifies estimates of $E_w$; a given value of $E_w$ is associated (in a dipole field) with a given slope in a sequence of data points, irrespective of the equatorial radius.

The path position data of Figure 1 were differentiated by determining the slope of a line least squares fitted to each 30 min of data for an individual path. A value of east-west electric field was obtained by averaging over results from all paths tracked in a given 30-min period. Successive 30-min periods were overlapped by 15 min. The resulting data were then processed to obtain 24-hour E field patterns relevant to the mean equatorial radius of the paths, i.e., about 4 $R_E$. Figure 2 represents a Fourier cosine analysis (dc and first five terms) of each day's data. The curves are plotted in terms of magnetic local time (UT - 5 hours) instead of universal time. Table 1 lists the coefficients of the harmonic series.

The results confirm the earlier findings of E field fluctuations with magnitudes of the order of 0.1 mV/m [Carpenter and Seely, 1976]. The fluctuations did not generally decay in amplitude from day to day during the prolonged quiet period. As noted in the earlier study, the faster, more repeatable flow events tended to occur on the dayside, althouth the time of outward drift activity (negative $E_w$) appeared to shift backward in time from day to day, being centered on $\simeq$1000 MLT on July 4 and on $\simeq$0500 MLT on July 7. This is consistent with the limited earlier evidence of a relation between the time of the outward drift activity and the duration of preceding quieting. Drifts after dawn tended to occur in the immediate aftermath of moderate disturbances, while those before dawn tended to be preceded by several days of quiet [Carpenter and Seely, 1976]. As Table 1 indicates, the shift was accompanied by changes in the relative amplitude of the several terms in the harmonic series. On July 4 the semidiurnal term was largest, while on July 7 the largest term was diurnal.

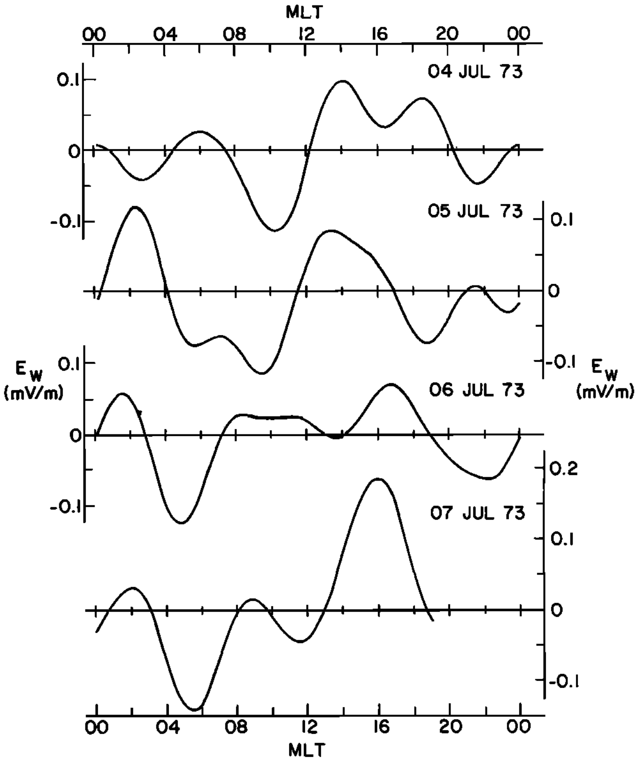

Fig. 2. The westward magnetospheric electric field near L = 4 deduced from the path radius data partially displayed in Figure 1. The data were analyzed in 24-hour blocks of MLT except for the case of July 7, in which the UT day was used. The dc and first five terms of a Fourier cosine series are plotted.

*Variations in $E_w$ with equatorial radius.* The results of $E_w$ on Figure 2 represent averages over all available path radii. However, there were periods of drift activity on paths spaced up to $\simeq$1 $R_E$ in equatorial radius; these present the possibility of measuring $E_w$ versus $R_{eq}$. Examples are the periods near 1000 MLT on July 4 (Figure 1a) and near 0900 MLT on July 5 (Figure 1b). Figures 3 and 4 show expanded views of the path data for these periods; The data points from individual paths are now connected, and all available data are shown.

For the study of $|E_w|$ versus $R_{eq}$, intervals of $\simeq$1-hour duration such as those marked 1, 2, and 5 in Figures 3 and 4 were selected for analysis. It was required that drifts of 100 m/s or greater ($|E_w| \gtrsim 0.05$ mV/m) be present on paths distributed over $\Delta R_{eq} \simeq 1$ $R_E$. Above this lower limit, uncertainty in $E_w$ due to scaling errors tends to be of the order of $\pm$20% (see later paragraph) and should in many cases be smaller than the effects being measured. It was also required that all the multipath flows be in the same sense, inward or outward, and that the flows be well established at the time of the measurements. The objective here was to avoid complexities due to temporal and spatial structure of the fields and to lack of information on the east-west component of drift. The times of the selected intervals are listed in Table 2.

For each interval the electric field for each

TABLE 1. Fourier Cosine Analysis of $E_w$

| Date | $c_1$ | $\omega_1$ | $c_2$ | $\omega_2$ | $c_3$ | $\omega_3$ | $c_4$ | $\omega_4$ | $c_5$ | $\omega_5$ | $a_o/2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| July 4 | 0.037 | 263.0 | 0.045 | 128.0 | 0.028 | -75.2 | 0.035 | 56.4 | 0.016 | -33.8 | -0.00117 |
| July 5 | 0.022 | 303.8 | 0.078 | 61.1 | 0.014 | 220.0 | 0.028 | 137.0 | 0.028 | 180.0 | -0.00757 |
| July 6 | 0.035 | 218.0 | 0.016 | 36.3 | 0.054 | 53.6 | 0.017 | 94.4 | 0.019 | 160.0 | -0.00667 |
| July 7 | 0.073 | 240.1 | 0.050 | 166.0 | 0.062 | 182.0 | 0.032 | 68.0 | 0.011 | 139.0 | -0.00242 |

$$E_w = a_{o/2} + \Sigma_{k=1}^{5} c_k \cos\ (15kt - \omega_k).$$

Here t is magnetic local time in hours. The arguments of the cosines are in degrees measured eastward from midnight, and $E_w$ is in millivolts per meter. Calculations for July 7 were made for the UT day; the results were then displayed in MLT.

whistler path was calculated from a least squares linear fit to its position data; this electric field was identified with the equatorial radius of the path at the midpoint of the time interval. The results for the seven cases are plotted in Figure 5 in coordinates of $\log_{10} |E_w|$ versus $\log_{10} R_{eq}$. Dashed and solid lines represent $E_w > 0$ and $E_w < 0$, respectively. In each case there is a decreasing trend in $|E_w|$ with increasing $R_{eq}$. Typically, the falloff is by a factor of $\approx 2$ over $\approx 1$-$R_E$ distance.

The path data marked with an arrow in Figure 3 were omitted from the analysis of interval 2. These data appear to be delayed in phase by 1-2 hours with respect to the other cases. The case is believed to represent propagation at a longitude separated by 10°-20° from the longitude of the main sets of paths. This interpretation is supported by differences of 20-30% between magnetospheric electron density levels deduced from the 'on-meridian' and 'off-meridian' components.

A thorough analysis of uncertainty in the method of determining $|E_w|$ remains to be done. However, there is evidence that such uncertainty is substantially smaller than the scale of the variations in $|E_w|$ with $R_{eq}$ shown in Figure 5. For example, the data on $|E_w|$ versus $R_{eq}$ for the essentially consecutive time intervals 1 and 2 of Figure 3 exhibit similar behavior. In the case of interval 5 (Figure 4), $|E_w|$ values were obtained from three paths closely spaced in $R_{eq}$. The values differ from one another by amounts small in comparison with the overall variation in $|E_w|$ with $R_{eq}$ inferred for that time.

The $E_w$ values were calculated by assuming a dipole field model. When the effects of quiet time ring currents are considered, there is a decrease of the order of 10% in the deduced $E_w$ values near L = 4 [Seely, 1977]. However, the variations with L in the effect are not believed to be large enough to explain the 2-to-1 changes observed. Furthermore, ring current effects would be expected to decay from day to day during prolonged quiet. Such a decay is not observed in the drift activity.

## 4. Discussion and Concluding Remarks

Dynamo effects in the magnetosphere. The theoretically expected variation of the magnitude of dynamo-induced electrostatic fields was summarized by Mozer [1973] as a slow increase with latitude at ionospheric heights. For comparisons with the results reported here the increase is slow enough to be approximated by a constant over the latitude range represented by the data of Figure 5. An east-west field constant with L at ionospheric heights maps to the equator as $R_{eq}^{-3/2}$ in a dipole magnetosphere [e.g., Mozer, 1970]. Figure 5 shows a line corresponding (in slope) to this behavior; the observed fields tend to fall off more steeply than this, the average for the seven cases being $\approx R_{eq}^{-4}$. This implies that at ionospheric heights the field on average falls off near L = 4 as $L^{-5/2}$.

The falloff suggests that the observed quiet time fields originate at L < 4, where dynamo-associated forces are strongest. This provides additional support for the concept that quiet time plasmaspheric electric fields are predominantly of dynamo origin. The east-west fields of approximately 0.1 mV/m near L = 4 reported here are below the amplitudes predicted by dynamo theory by a factor of about 2 [e.g., Scheildge, 1974; H. Maeda, 1970]. This may be partly the result of the reported falloff, however; the slope of the $|E_w|$ curves in Figure 5 suggests that theory and observations of $E_w$ may be in relatively good agreement at $L \lessapprox 3.5$.

By extrapolating from Figure 5 it is concluded that east-west fields with fluctuation amplitudes of 0.2 mV/m at the equator regularly exist near L = 3. These fields, apparently of dynamo origin, are (as noted by Carpenter and Seely [1976]) within a factor of 2-3 in amplitude of the east-west fields that penetrate the plasmasphere during substorms.

The fact that dynamo theory does not predict a falloff in electric field at L ≃ 4 is not surprising. The theory was not developed to deal with relatively small scale features, nor with the purpose of making predictions of magnetospheric effects at latitudes above about 60°. The interplay between the dynamo and the effects of high-latitude sources of heat, ionization, and electric fields has only recently begun to be examined.

It is possible that the time-dependent state of the subauroral ionosphere near and above 60° latitude is important in producing the falloff.

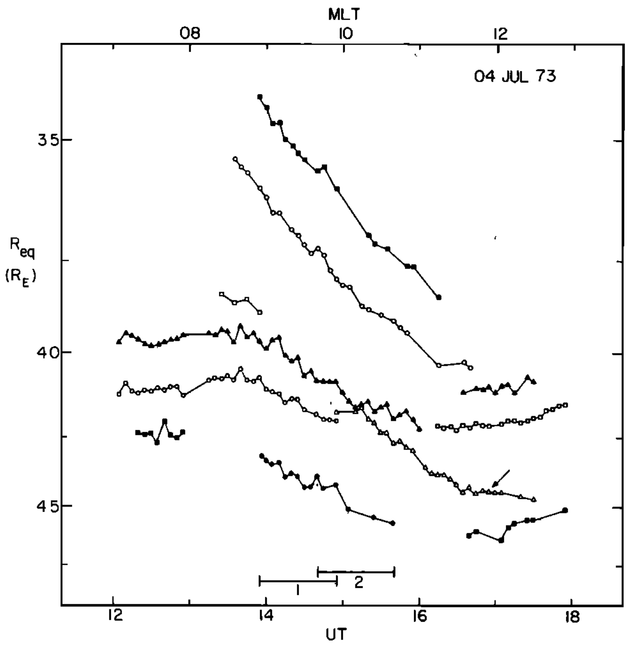

Fig. 3. Whistler path equatorial radii during a several-hour period on July 4, 1973, showing an apparent decrease in $E_w$ with increasing equatorial radius. The nonlinearity of the path radius scale is such that the slope of a data curve is proportional to $E_w$ independent of path radius (for a dipole magnetic field). The various symbols are associated with individual whistler components.

That is, there may be latitudinal variations in conductivity and related structure that effectively shield the dynamo field from the region beyond L = 4. Possible evidence of such an effect may appear in Figure 5, in which the observing intervals are numbered chronologically (see also Table 2). The most rapid falloffs occurred in the first two days of the quiet period. On the last two days (cases 6 and 7) the slope is relatively gradual and close to the behavior expected if the field were roughly constant with latitude at ionospheric heights.

*The noon-midnight asymmetry*. Gringauz and Bezrukikh [1976] have used Prognoz satellite data to identify a noon-midnight quiet time asymmetry in the plasmasphere. The drift patterns illustrated in Figure 1 suggest such an effect; a secondary maximum in plasmasphere radius should occur near local noon, when the drifts on average reverse from outward to inward. While relatively small in amplitude (≈200 m/s near L = 4), the drifts are long enduring; Figure 1 suggests that the noontime plasmasphere radius may be of the order of 1 $R_E$ larger than the radius in the dawn sector. (Some preliminary indication of this effect was reported in early studies of the plasmapause [Carpenter, 1966]. From 12 days of analysis during recovery periods it was found that a secondary maximum in plasmapause radius occurred near noon. The maximum found was not a pronounced one, owing to mixing of data representing various degrees of magnetic activity; however, it is believed to reflect the quiet day effect.) Thus it appears that while substorm fields may dominate the outer plasmasphere during disturbed periods, fields of dynamo origin may play a major role during quieting, giving

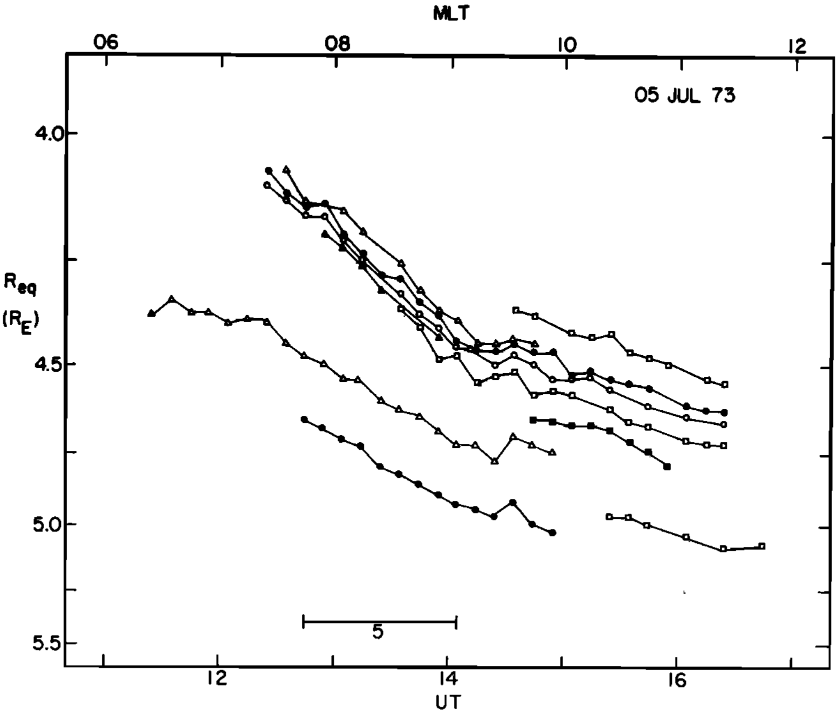

Fig. 4. Whistler path equatorial radii during a several-hour period on July 5, 1973, showing an apparent decrease in $E_w$ with increasing equatorial radius.

TABLE 2. Times of $E_W$ versus L Measurements

| Interval No. | Date in 1973 | Time, UT |
|---|---|---|
| 1 | July 4 | 1355-1455 |
| 2 | July 4 | 1440-1540 |
| 3 | July 4 | 1715-1805 |
| 4 | July 4 | 2040-2200 |
| 5 | July 5 | 1245-1405 |
| 6 | July 6 | 0925-1020 |
| 7 | July 7 | 2045-2145 |

rise to plasmaspheric features such as the noontime bulge (possible solar magnetospheric causes of the bulges were considered by Gringauz and Bezrukikh 1976 ). Because it represents tilting of the plasmapause across L shells, the noon bulge may be penetrated by drifting energetic particles, a process which may result in generation of ULF and VLF waves, heating of the outer plasmasphere, and particle precipitation into the ionosphere.

Much remains to be done in the area of quiet time plasmaspheric structure and dynamics. There is a need to measure quiet time magnetospheric drifts on a worldwide basis. Such mapping may provide a quiet time model of plasmaspheric electric fields for use in studies of the penetration of substorm and magnetic storm fields into middle magnetospheric regions. There is a need to investigate further the reported relation between the time of outward drift activity and the duration of preceding quieting. The data supporting this relationship are not yet sufficient to be persuasive; day-to-day variability in the dynamo process may contribute to or dominate the reported effects.

Spatial variations in the quiet day electric field should be studied, hopefully over ranges extending to L values of 3 or lower. Fortunately, whistler rates are relatively high at ground stations near L = 3-4 during quieting or quiet; thus important progress on these topics during the multistation campaigns of the International Magnetospheric Study may be expected.

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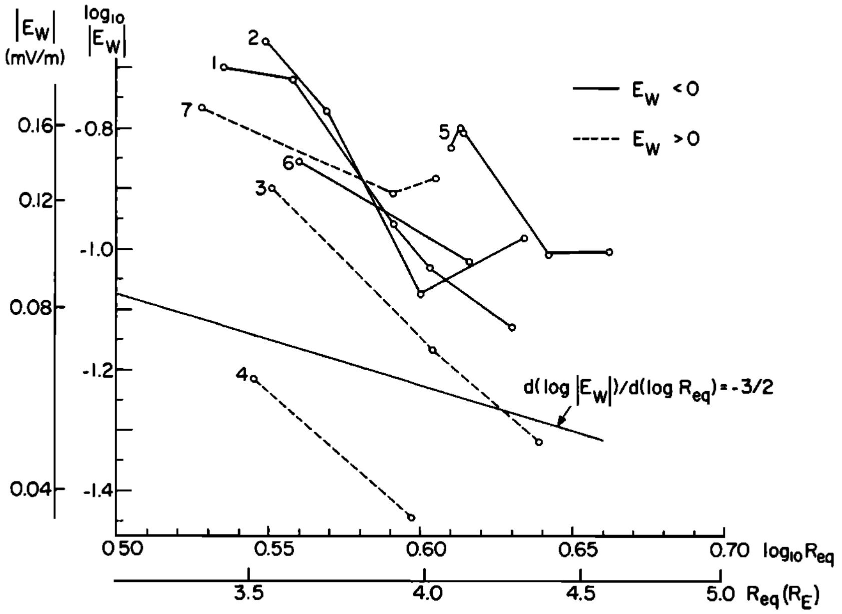

Fig. 5. Variation of the magnitude of the magnetospheric westward electric field $E_W$ with equatorial radius, in coordinates of $\log_{10} |E_W|$ versus $\log_{10} R_{eq}$. Values of $E_W$ were deduced from path position data of the type illustrated in Figures 3 and 4. The seven cases correspond to the intervals listed in Table 1 (intervals 1, 2, and 5 are marked in Figures 3 and 4). The solid line represents (by its slope) the expected falloff in $E_W$ with $R_{eq}$ if an east-west electric field at ionospheric heights were mapped upward to the equator in a dipole magnetic field.

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