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WHISTLER OBSERVATIONS OF SUBSTORM ELECTRIC FIELDS IN THE NIGHTSIDE PLASMASPHERE

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Abstract. Whistlers recorded in the Antarctic were used to infer the east-west component of electric field in the nightside plasmasphere between L ~ 3 and 6 during moderate substorms. The results show eastward electric fields of ~0.2 *mV/m* in the equatorial plane in the premidnight local time sector. Near midnight there is a sharp transition from these eastward fields to westward fields of ~0.2-0.6 *mV/m*. The existence of westward substorm fields in the postmidnight sector has been reported in several previous papers as a prominent feature in the whistler data. These fields are distinct from quiet time fields that are directed eastward over the entire nightside and have an average magnitude of ~0.05 *mV/m*. The substorm electric field pattern described here is consistent with previous ionosonde observations of large-scale distortions of the nightside F layer showing an uplifting in the premidnight sector and a lowering in the postmidnight sector.

Introduction

The whistler technique has been used for many years to measure electric fields (east-west component) in the plasmasphere during substorms as well as during quiet times [Carpenter and Stone, 1967; Carpenter et al., 1972; Carpenter and Seely, 1976; Carpenter and Akasofu, 1972; Park, 1976]. The technique has been examined by Block and Carpenter [1974].

Early results showed that the most pronounced feature of substorm electric field in the midlatitude plasmasphere is a westward field of up to ~1 *mV/m* in the equatorial plane in the postmidnight sector. This field is sharply confined between ~0000 and 0400 magnetic local time (MLT), although the boundaries may move by ~1 hr in either direction in individual storms. At the dawnside boundary the electric field frequently reverses its direction and becomes eastward if substorm activity subsides rapidly [Carpenter and Stone, 1967; Park and Carpenter, 1970; Carpenter and Akasofu, 1972], but the picture in the premidnight sector has remained unclear. It is the purpose of this brief report to describe whistler observations of substorm electric fields in the premidnight sector.

This report deals only with specific substorm features in middle latitudes and in a limited time sector. For a more general review of magnetospheric electric fields the reader is referred to recent review papers by Stern [1977] and Fairfield [1977].

Observations

Whistlers used in this study were recorded at Eights (75°S, 77°W) and Siple (76°S, 84°W) in Antarctica. In each of the four case studies described below, individual whistler ducts were identified on broadband spectrograms, and their cross-L motions deduced from observed changes in nose frequencies. The whistler nose frequency f_n is related to its path L value by

$$f_n \simeq 3.23 \times 10^5 L^{-3} \quad (1)$$

where f_n is given in hertz and a centered dipole magnetic field has been assumed. In the equatorial plane the convection electric field, defined as positive in the eastward direction, is given by

$$E = \frac{-v \times B}{B^2} = -2.1 \times 10^{-2} \left(\frac{d f_n^{2/3}}{dt}\right) \text{ V/m} \quad (2)$$

For a more detailed discussion of the whistler technique the reader is referred to the references cited in the previous section.

June 9, 1965 Case

The results of this case study are summarized in Figure 1. The top panel shows the auroral electrojet (AE) index plotted against UT as an indicator of substorm activity level. In the bottom panel the vertical scale on the left is linear in the two-thirds power of whistler nose frequency (f_n), while the right hand scale shows the corresponding equatorial path radius. This choice of scales was made so that a straight line on the plot would indicate a constant electric field (see (2)). Each series of closely spaced dots, circles or triangles represents a particular whistler duct whose nose frequency could be measured as a function of time. The whistler data came from Eights.

The AE index started from ~450 γ at 0000 UT, dipped down to ~150 γ between 0030 and 0130 UT, and increased up to ~400 γ before dropping again to a very low level of ~50 γ at 0400 UT. During this substorm activity, Eights was in the premidnight MLT sector, and the outward drift of whistler ducts indicated an eastward electric field of ~0.2 *mV/m* in the equatorial plane. Between 0400 and 0600 UT the AE index remained low, and there was no detectable duct motion. At ~0600 UT the AE index surged to a sharp peak, followed by a relatively steady level at ~200 γ. By 0600 UT, Eights was at 0100 MLT, and the response to this postmidnight substorm activity was a rapid inward drift of ducts, corresponding to a westward electric field of ~0.3 *mV/m*. This inward drift terminated abruptly at ~0900 UT, or 0400 MLT.

The westward field in the postmidnight sector has been well documented in the references cited in the introduction. The new feature we wish to emphasize here is the eastward field in the premidnight sector.

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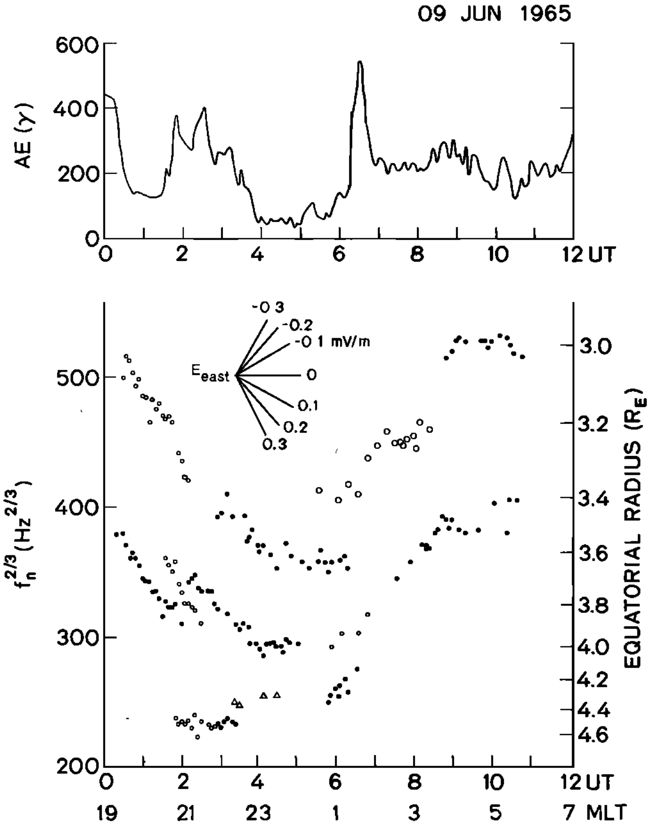

Fig. 1. (Top) Auroral electrojet index versus universal time and (bottom) variations of whistler nose frequency (plotted on a linear scale in the two-thirds power of nose-frequency) and corresponding equatorial crossing radius. The whistlers were recorded on June 9, 1965, at Eights, Antarctica, whose magnetic local time is about 5 hours behind UT. Each series of data points in same symbol represents a distinct whistler duct that could be tracked in time. A straight line in this plot indicates a constant east-west electric field in the equatorial plane, as indicated by the slope of calibration diagram.

July 23, 1973 Case

This case is illustrated in Figure 2 in the same format as Figure 1. The whistler data for this, as well as all subsequent case studies, came from Siple. The AE index started to increase at 0100 UT and remained at moderate levels throughout the period shown. Whistler ducts showed no drift until about 0230 UT, outward drifts from 0230 to 0530 UT, and then rapid inward drifts from 0530 to 0610 UT. This pattern corresponds to no electric field until 2130 MLT, an eastward field of ~0.2 *mV/m* between 2130 and 0030 MLT, and a westward field of 0.6 *mV/m* between 0030 and 0110 MLT. Again the westward field in the postmidnight sector is consistent with earlier results. The new result is the existence of an eastward electric field in the premidnight sector.

June 16, 1973 Case

Figure 3 illustrates the third case, in which the AE index started out at a moderate level of ~250 γ, increased to ~400 γ at 0200 UT, and then decreased steadily down to ~50 γ to 0440 UT, at which time the decreasing trend had changed to a gradual increase. Whistler drift data were not available until about 0230 UT, or 2130 MLT at Siple. At 0230 UT the AE index is ~300 γ, and the whistler duct drifts indicated an eastward electric field of ~0.2 *mV/m*. This field persisted until ~0345 UT, or 2245 MLT, when the AE index had dropped to ~150 γ. No significant drift was observed after 0345 UT.

July 18, 1973 Case

The results of this case study are illustrated in Figure 4. The AE index had two peaks, one starting near 0200 UT and the other near 0400 UT. There was no evidence of whistler duct drift until about 0220 UT, or 2120 MLT, at which time an outward drift, corresponding at a ~0.2 *mV/m* eastward electric field, set in. This drift lasted until 0300 UT, or 2200 MLT, when the AE index dropped to ~120 γ. During the following hour the AE index remained low, and the whistler ducts showed slight inward drifts. The corresponding electric field would be ~0.05 *mV/m* westward. Near 0400 UT, or 2300 MLT, the AE index started increase toward another moderate peak of ~350 γ, and the westward electric field increased to 0.1 *mV/m*.

Summary

The substorm electric field in the plasmasphere between L ≃ 3 and 6 is found to be directed westward in the postmidnight sector, in agreement with previously published results. By contrast, the substorm field in the premidnight sector is generally eastward. The magnitude of the

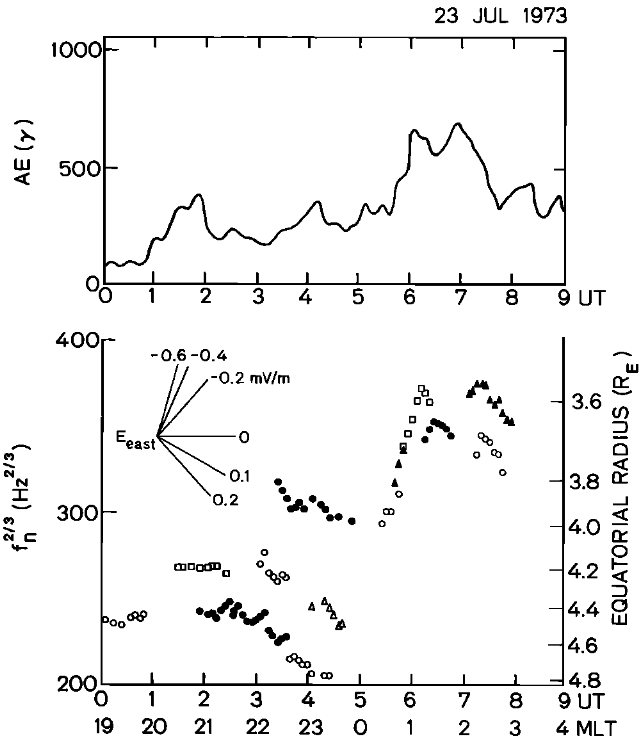

Fig. 2. A case study in the same format as Fig. 1. The whistlers in this case were recorded at Siple, Antarctica on July 23, 1973.

eastward field is about 0.2 *mV/m* in the equatorial plane, and it does not appear to be sensitive to the substorm intensity within the limited AE index range of ~100-400 γ covered in the above case studies. In two of the four cases shown above (Figures 2 and 4) the eastward field appeared suddenly at ~2130 MLT, even though substorm activity commenced prior to this time. This suggests a rather sharp spatial transition in the east-west component of substorm field at ~2130 MLT. In Figure 1 the eastward field appeared as early as 1930 MLT, when the data coverage started. In Figure 3 the data coverage is insufficient to tell when the eastward field first appeared.

Discussion

A previous study has shown that substorm electric field has an eastward component of ~0.2 *mV/m* in the 1600-2000 MLT sector [Park, 1976]. Whistler duct drifts were found to terminate abruptly near 2000 MLT, even in cases where substorm activity persisted beyond that time. In the present study, Figures 2 and 4 show that the premidnight eastward field did not appear until the observing station reached ~2130 MLT, even though substorm activity started before that time. (In Figure 1, however, the eastward field appeared as early as ~1930 MLT.) These results suggest that the premidnight eastward substorm field does not extend into the dusk sector and connect with the previously reported eastward field in the ~1600-2000 MLT sector [Park, 1976]. The two eastward fields appear to be separate features, as is illustrated in Figure 5.

Figure 5 shows whistler drift data from Siple for June 14-15, 1973. The AE index rose slightly at 2030 UT and remained near or slightly above the 300-γ level until ~0630 UT. The whistler data show an eastward electric field of ~0.2 *mV/m* between ~1530 MLT and ~2000 MLT but no significant field from ~2000 MLT to 2200 MLT. The data up to 2130 MLT were shown in Figure 1b of Park [1976]. In the present study, whistler

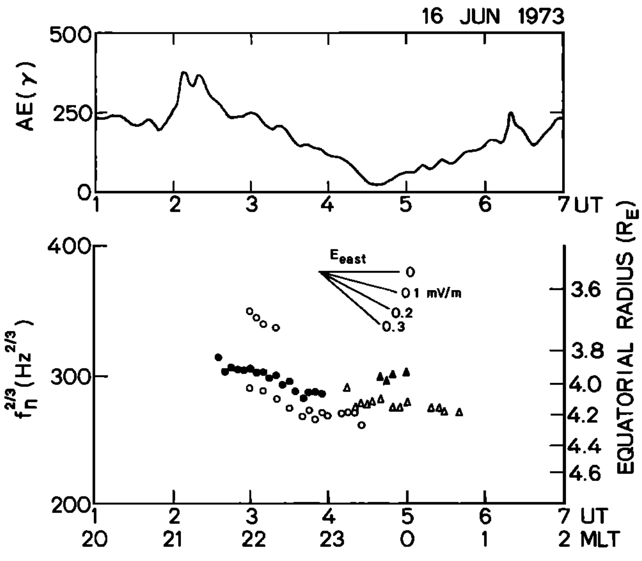

Fig. 3. A case study using Siple whistlers from June 16, 1973, in the same format as Figure 1.

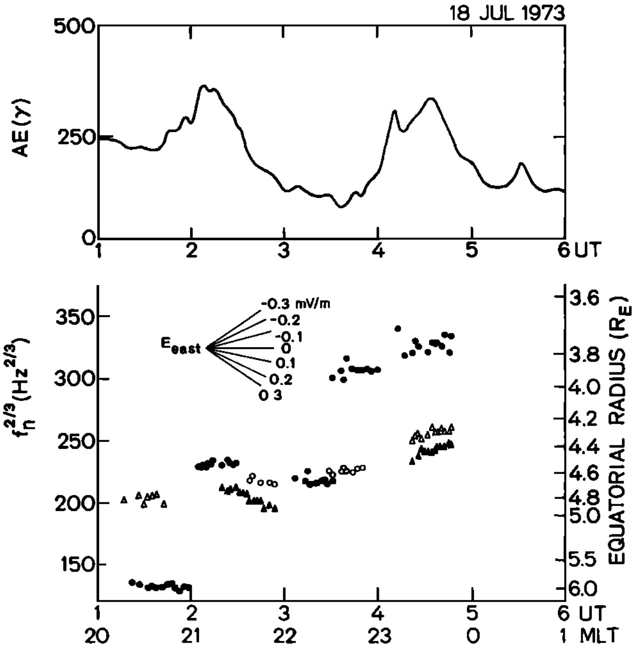

Fig. 4. A case study using Siple whistlers from July 18, 1973, in the same format as Fig. 1.

data analysis was extended beyond 2130 MLT to reveal the reappearance of eastward electric field in the premidnight sector between ~2200 and ~0100 MLT.

We have assumed that the observed changes in whistler f_n were due to cross-L drift of ducts in a steady geomagnetic field. In a dynamic geomagnetic field, however, $\partial B/\partial t$ also contributes to $\partial f_n/\partial t$. These effects are clearly seen during sudden impulses and compressional oscillations in the magnetosphere [Block and Carpenter, 1974; Park, 1975]. Block and Carpenter [1974] showed that the $\partial B/\partial t$ effects due to changing ring current intensity can be estimated from low-latitude ground magnetograms. We examined magnetograms from Tucson and San Juan during the substorm cases presented in this paper and found no evidence of magnetic field fluctuations that could have contributed significantly to the observed variations in whistler nose frequencies. Our interpretation of the whistler data in terms of electric field appears to be valid to the first order.

The present results, showing a reversal of substorm electric field from eastward to westward near midnight, agree with the results of ionosonde observations of the nighttime F layer during substorms [Park & Meng, 1971,1973]. In the ionosonde studies, it was found that during the long nights of winter, the F layer in middle latitudes settles down to a quasi-steady state where it responds to magnetospheric substorm activity in a characteristic manner. The response is a large-scale distortion, with the F layer lifted upward in the premidnight sector and pushed downward in the postmidnight sector. This distortion was interpreted as the result of $\vec{E} \times \vec{B}$ drift by an eastward electric field before midnight and by a westward field after midnight. This reversal in the electric field direction is confirmed by the whistler results

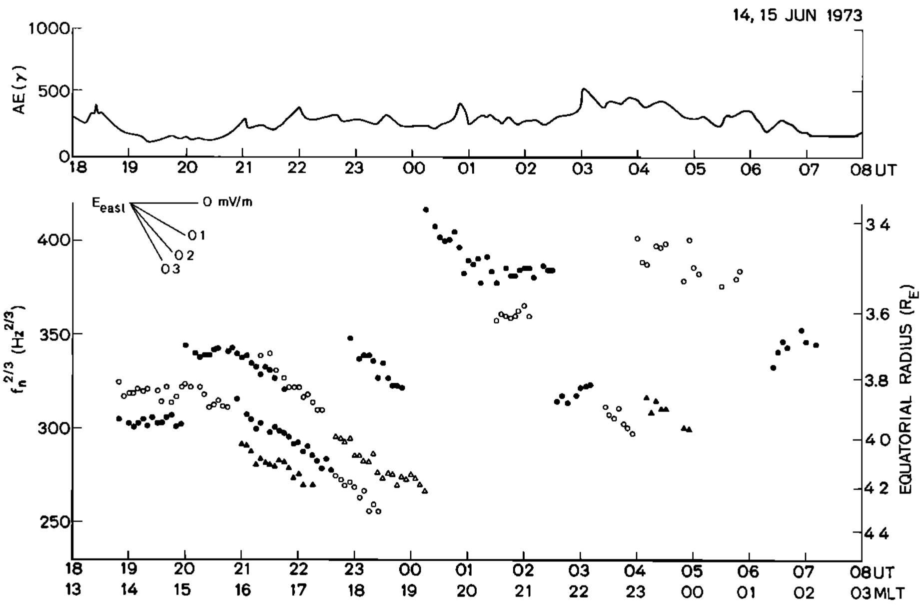

Fig. 5. A case study using Siple whistlers from June 14-5, 1973 in the same format as Figure 1.

reported here. Substorm electric fields reported here are distinct from quiet time electric fields that are directed eastward over the entire nightside and have an average magnitude of ~0.05 *mV/m* [Carpenter and Seely, 1976]. Recent results from the S3-2 satellite also confirmed that the substorm electric field has an eastward component in the premidnight sector near the plasmapause [Smiddy et al., 1977].

At auroral latitudes, electric fields are generally much stronger and more variable compared to those observed in the plasmasphere [e.g., Banks et al., 1973, 1974; Rino et al., 1974; Mozer, 1971; Mozer et al., 1973; Heppner, 1972; Cauffman and Gurnett, 1972; Haerendel, 1973; Spiro et al., 1978]. Furthermore, the penetration of auroral electric fields to middle latitudes depends strongly on the ionospheric conductivity distribution [Wolf, 1970] and on the shielding properties of energetic particles [Jaggi and Wolf, 1973; Vasyliunas, 1972]. For these reasons it is difficult to relate our observations of substorm electric field in middle latitudes to the observations made at auroral latitudes. It will be useful in future studies to make simultaneous observations of substorm electric fields at both auroral and middle latitudes.

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References

Banks, P. M., J. R. Doupnik, and S.-I. Akasofu, Electric field observations by coherent scatter radar in the auroral zone, J. Geophys. Res., 78, 6607, 1973.

Banks, P. M., C. L. Rino, and V. B. Wickwar, Incoherent scatter radar observations of westward electric fields and plasma densities in the auroral ionosphere, 1, J. Geophys. Res., 79, 187, 1974.

Block, L. P., and D. L. Carpenter, Derivation of magnetospheric electric fields from whistler data in a dynamic geomagnetic field, J. Geophys. Res., 79, 2783, 1974.

Carpenter, D. L., and S.-I. Akasofu, Two substorm studies of relations between westward electric fields in the outer plasmasphere, auroral activity, and geomagnetic perturbations, J. Geophys. Res., 77(34), 6854, 1972.

Carpenter, D. L., and K. Stone, Direct detection by a whistler method of the magnetospheric electric field associated with a polar substorm, Planet. Space Sci., 15(2), 395, 1967.

Carpenter, D. L., and N. Seely, Cross-L plasma drifts in the outer plasmasphere: Quiet time patterns and some substorm effects, J. Geophys. Res., 81, 2728, 1976.

Carpenter, D. L., K. Stone, J. C. Siren, and T. L. Crystal, Magnetospheric electric fields deduced from drifting whistler paths, J. Geophys. Res., 77, 2819, 1972.

Cauffman, D. P., and D. A. Gurnett, Satellite measurements of high latitude convection electric fields, Space Science Rev., 13, 369, 1972.

Fairfield, D. H., Electric and magnetic fields in the high-latitude magnetosphere, Rev. Geophys. Space Phys., 15, 285, 1977.

Haerendel, G., Results from barium releases in the ionosphere and magnetosphere, Space Res., 13, 601, 1973.

Heppner, J. P., Electric field variations during substorms: OGO-6 measurements, Planet. Space Sci., 20, 1475, 1972.

Jaggi, R. K., and R. A. Wolf, Self-consistent calculation of the motion of a sheet of ions

in the magnetosphere, J. Geophys. Res., 78, 2852, 1973.
Mozer, F. S., Origin and effects of electric fields during isolated magnetospheric substorms, J. Geophys. Res., 76, 7595, 1971.
Mozer, F. S., F. H. Bogott, and B. Tsurutani, Relationships between ionospheric electric fields and energetic trapped and precipitating electrons, J. Geophys. Res., 78, 630, 1973.
Park, C. G., Whistler observations during a magnetospheric sudden impulse, J. Geophys. Res., 80, 4738, 1975.
Park, C. G., Substorm electric fields in the evening plasmasphere and their effects on the underlying F layer, J. Geophys. Res., 81, 2283, 1976.
Park, C. G., and D. L. Carpenter, Whistler evidence of large-scale irregularities in the plasmasphere, J. Geophys. Res., 75, 3825, 1970.
Park, C. G., and C.-I. Meng, Vertical motions of the mid-latitude F_2 layer during magnetospheric substorms, J. Geophys. Res., 76, 8326, 1971.
Park, C. G., and C.-I. Meng, Distortions of the nightside ionosphere during magnetospheric substorms, J. Geophys. Res., 78, 3828, 1973.
Rino, C. L., V. B. Wickwar, P. M. Banks, S.-I. Akasofu, and E. Rieger, Incoherent scatter radar observations of westward electric fields, 2, J. Geophys. Res., 79, 4669, 1974.
Smiddy, M., M. C. Kelley, W. Burke, F. Rich, R. Sagalyn, B. Shuman, R. Hays, and S. Lai, Intense poleward-directed electric fields near the ionospheric projection of the plasmaspause, Geophys. Res. Letts., 4, 543, 1977.
Spiro, R. W., R. A. Heelis, and W. B. Hanson, Ion convection and the formulation of the mid-latitude F region ionization trough, J. Geophys. Res., 83 (A9),4255, 1978.
Stern, D., Large-scale electric fields in the earth's magnetosphere, Rev. Geophys. Space Physics, 15, 156, 1977.
Vasyliunas, V. M., The interrelationship of magnetospheric processes, in Earth's Magnetospheric Processes, edited by B. M. Mc Cormac, p.294, D. Reidel, Hingham, Mass., 1972.
Wolf, R. A., Effects of ionospheric conductivity on convective flow of plasma in the magnetosphere, J. Geophys. Res., 75, 4677, 1970.

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