DRIFT SPIKES: THE IONOSPHERIC SIGNATURE OF LARGE POLEWARD DIRECTED ELECTRIC FIELDS AT SUBAURORAL LATITUDES

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***Abstract*:** A VHF doppler auroral radar operating in the south of New Zealand since early 1978 has quite frequently observed long persisting echoes with large doppler shifts over a limited range interval. These are confined to dark hours, are primarily in the premidnight sector, lie between 58°S and 62°S invariant, and closely follow the onset of the expansive phase of substorms. There seems little doubt that they are the ionospheric signature of the large poleward directed electric fields observed in the *F* region by AE-C, S3-2 and OGO-6, although no direct confirmation has yet been possible. We have called these phenomena "drift spikes".

The characteristics of the auroral radar data are described and related to magnetic and ionosonde data from Campbell Island at 60.1°S invariant. It is shown that drift spikes occur in the *F* region trough on the equatorward edge of the easterly electrojet, which itself decays as the spike develops. In some degree the spike may reflect the behaviour of the westerly electrojet at high latitudes.

1. Introduction

In recent years there have been several observations by low orbiting satellites of very large westward ion drifts in the subauroral region in the pre-midnight sector (Heelis *et al.*, 1976; Smiddy *et al.*, 1977; Maynard, 1978; Spiro *et al.*, 1978). They exist over only a degree or so of latitude and can persist for up to two hours. We shall call these phenomena "drift spikes". In their investigation of the high latitude convection pattern leading to the formation of the ionospheric trough Spiro *et al.* (1978) sometimes found drift spikes near the sharp poleward edge of the trough. They were thought to be substorm related.

Since the establishment of a new auroral radar with doppler capability in the south of New Zealand early in 1978 (Keys and Johnston, 1979) we have quite often observed what appears to be the ionospheric signature of drift spikes.

The map in Fig. 1 shows the radar beam. Echoes from field-aligned electron density irregularities can be observed between about 350 km slant range and the *E*-region horizon, that is from $L \sim 3.5$ to $L \sim 5.9$. The line of sight is oriented about

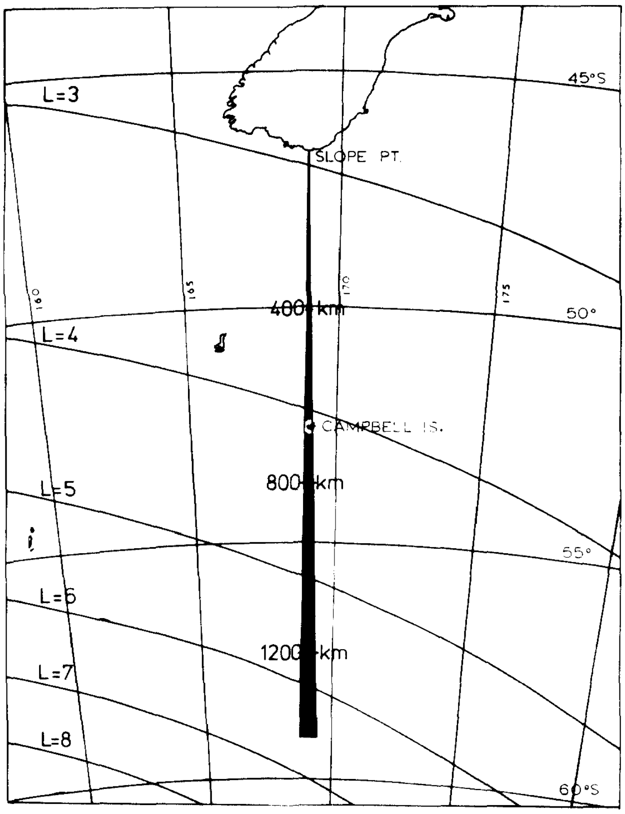

Fig. 1. Coverage of Slope Point auroral radar. Beamwidth is to half-power points and slant ranges to a haight of 110 km.

20° east of the magnetic meridian, so irregularities drifting westward along L shells will give a positive doppler shift to radar echoes. We shall be comparing radar data with that from various geophysical instruments on Campbell Island, at $L=4.1$.

Radar data is displayed on a CRT and recorded on 35 mm film as a range/time/amplitude record above a range/time/mean doppler velocity record. Examples are given in Figs. 2 and 3. Range boxes are 10 km long and data is displayed following 20-second integration periods indicated by the vertical lines. Signal amplitude is proportional to displacement of the CRT spot to the right of the zero line, mean doppler velocity to displacement to the right (positive or towards the radar) or left (negative or away from the radar). Full-scale displacement (corresponding to the length of the integration period on the time axis) occurs for mean doppler velocities of ± 1000 m s^{-1}. Velocities greater than ± 1000 m s^{-1} alias to the opposite sense giving quite a conspicuous effect on the record as seen at middle ranges in Figs. 2 and 3. These will be discussed later. For a detailed account of how the radar display is built up, see KEYS and JOHNSTON (1979).

2. Data

Figs. 2 and 3 show the development of drift spikes on two occasions in 1978.

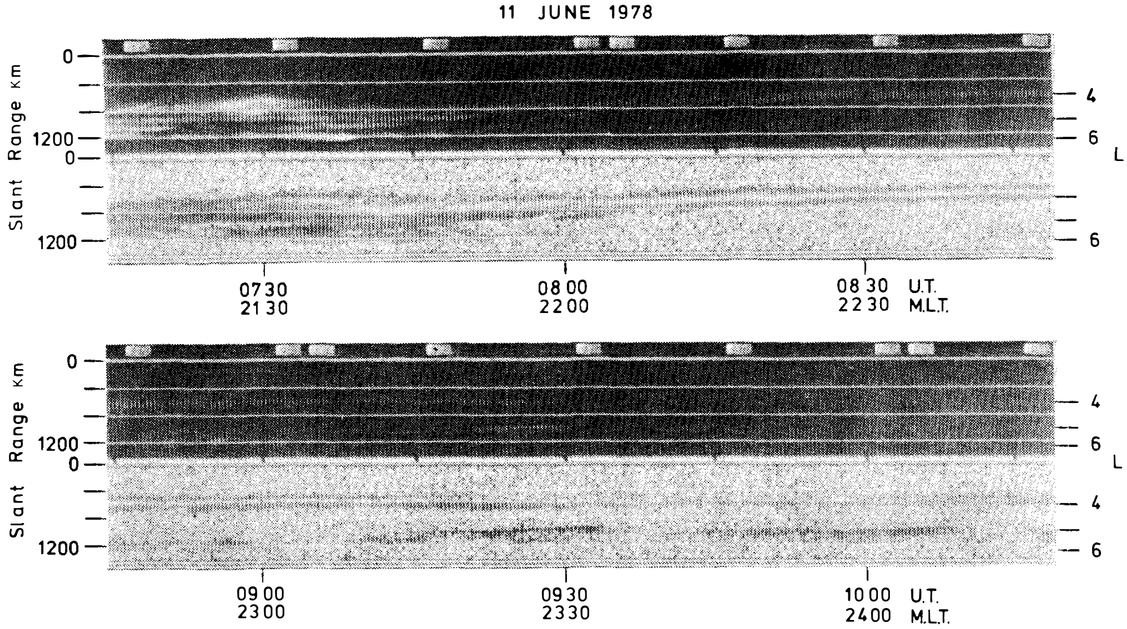

Fig. 2. *Radar display during the development of a drift spike on the evening of 11 June 1978. For explanation see text.*

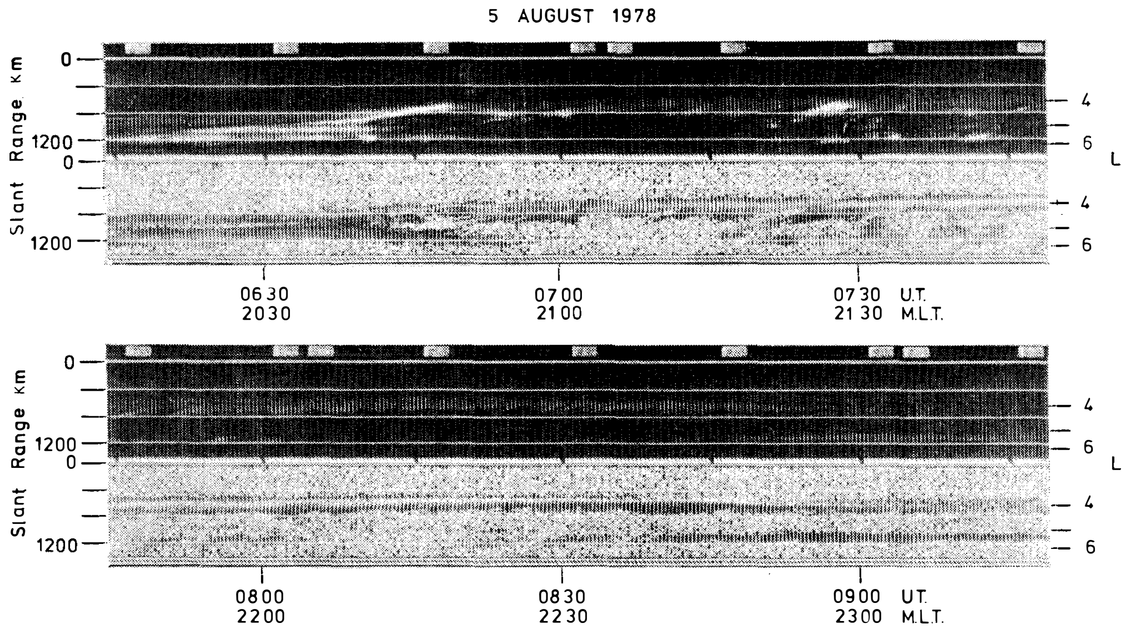

Fig. 3. *Radar display during the development of a drift spike on the evening of 5 August 1978. For explanation see text.*

The echoes at the left of the upper panels in each figure are typical late evening diffuse, the type arising from the easterly electrojet (GREENWALD *et al.*, 1975). We interpret the mean doppler velocity, up to several hundred metres per second, as the line of sight component of the (westward) Hall drift velocity of electrons in the electrojet (ECKLUND *et al.*, 1977). As time progresses the maximum doppler velocity develops near the equatorward edge of the echo region. Then all echoes rapidly become weak, with those at longer range disappearing and the shorter range ones showing an increasing maximum doppler velocity and an irregular and slow equatorward migration. Towards the right of the top panels of Figs. 2 and 3 the maximum doppler velocity exceeds 1 kilometre per second (note aliasing) and approaches 2 km per second a little later. The equatorward migration continues to about half-way along the bottom panel in each figure, after which it tends to reverse, the peak velocities decrease and the spikes decay shortly after. Early in the life of the spikes the velocity profiles are approximately symmetrical, with about 50 km width at half amplitude; towards the end the profiles are much steeper on the equatorward side and the half-widths are down to about 20 or 30 km.

A peak doppler velocity of 2 km s^{-1} in the radar line of sight corresponds to a westward electron drift along an L shell of about 6 km s^{-1}. The corresponding electric field is 370 mV m^{-1} directed poleward. Comparable values were inferred from the satellite observations (SMIDDY *et al.*, 1977; MAYNARD, 1978; SPIRO *et al.*, 1978). The slow equatorward migration, increasing peak velocity, and narrowing of the drift spike with time were also observed. There seems little doubt that the radar and satellites were observing different manifestations of the same phenomenon.

Fig. 4 shows the duration, with a rough indication of the peak doppler velocity, of drift spikes observed over a 14-month period. Dotted lines are peak velocities less than 500 m s^{-1}, heavy bands peak velocities greater than 1 km s^{-1}. *Kp* sum is shown along the bottom, when no sum is shown the radar was not operating. It is clear from this figure that drift spikes:

(1) occur only when the *E*-region is in darkness;

(2) almost always start before magnetic midnight ($\sim$1000 hr UT);

(3) may persist for several hours after magnetic midnight;

(4) have a typical duration of one to two hours;

(5) have little relationship with the magnitude of *Kp* sum, although they invariably follow a period of evening diffuse echoes (as shown at the top left of Figs. 2 and 3) which are themselves related to *Kp* (UNWIN, 1966).

The range of invariant latitude covered by the peak doppler velocity between the beginning and the end of the spike is shown in Fig. 5 for all cases, plotted in order of decreasing latitude of their first appearance. The horizontal dashed lines represent the range limits of echo detection. Although there may be occasional loss of echoes at near ranges, the distribution shown is considered to contain no serious observational bias. The latitudes covered are appropriate to the *F*-region trough. The average equatorward movement of the spike during its lifetime is 1.4° of latitude.

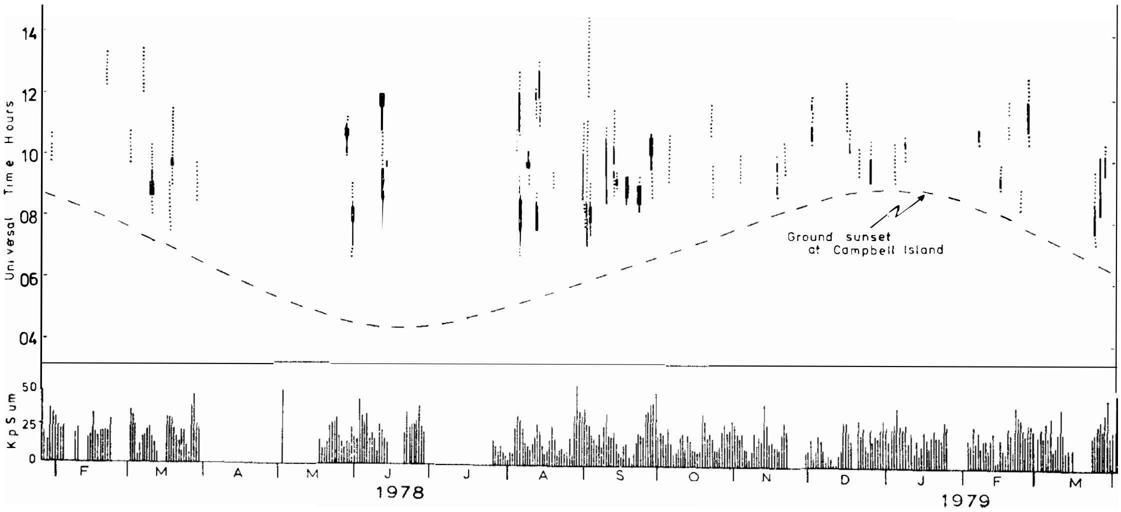

Fig. 4. Drift spikes observed from Slope Point, 27 January 1978 – 1 April 1979. Dotted sections, peak velocity (V_{max})<500 *m* s^{-1}; *full line sections, 500 m* $s^{-1} \leq (V_{max}) \leq$ *1000 m* s^{-1}; *heavy bars,* $V_{max} > 1000$ *m* s^{-1}. *Lower section, Kp sum (where no value is shown the radar was not operating).*

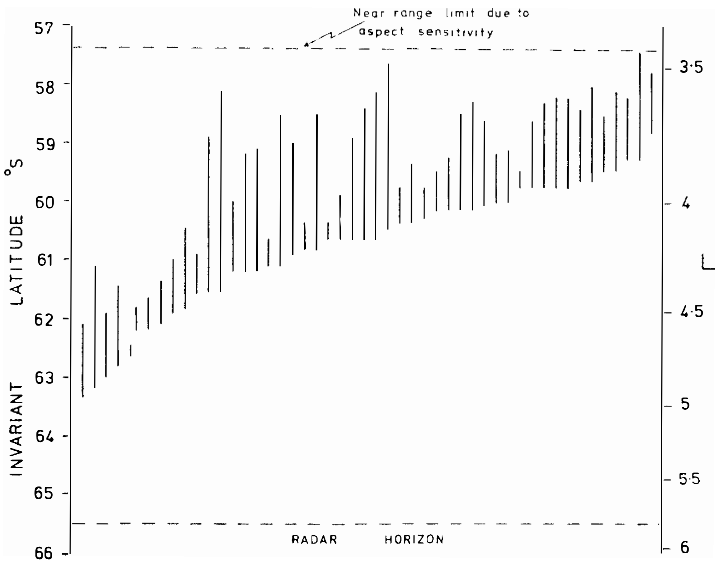

Fig. 5. Range of invariant latitude covered by drift spikes during their lifetime, plotted in order of decreasing latitude of their first appearance.

In two-thirds of cases the radar record showed features characteristic of the onset of the expansive phase of a substorm (UNWIN and KEYS, 1975) shortly before the development of the drift spike. In nearly all cases the magnetic records from Campbell Island and Macquarie Island (700 km south-west of Campbell Is.) also showed a substorm expansive phase onset. The delay to the development of the drift spike varied between 15 and 45 min in 85% of cases, with extremes of 10 min and 70 min. The average was 30 min.

3. Discussion

The radar observations indicate that drift spikes occur at a latitude appropriate to the *F*-region trough, and follow substorms with an average delay of tens of minutes. It is now well established that in the premidnight sector the trough lies immediately equatorward of the easterly electrojet. Following the onset of a substorm expansive phase the westerly jet penetrates westward round the auroral oval, on the poleward side of the easterly jet. This penetration may be irregular during the expansive phase (WIENS and ROSTOKER, 1975). Downward and upward field-aligned currents are associated with the easterly and westerly electrojets respectively. The signature of the three-dimensional current system on ground magnetometers has recently been well documented by HUGHES and ROSTOKER (1979) and ROSTOKER and HUGHES (1979).

Fig. 6 shows the Campbell Island magnetic records covering the periods of the drift spikes shown in Figs. 2 and 3. The spikes migrate equatorward over Campbell Island at approximately 0815 UT and 0730 UT respectively. In both

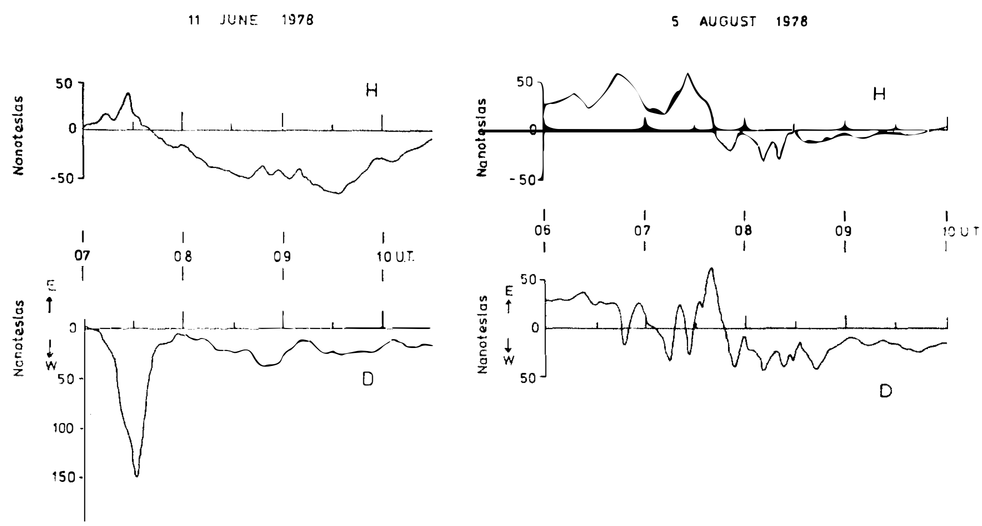

Fig. 6. Magnetic records from Campbell Island covering periods of drift spikes illustrated in Figs. 2 and 3.

cases, before the development of the spike proper, there is good correlation between the amplitude of the positive H deviation and echo amplitude, a result in accord with previous studies of the diffuse radio aurora and eastward electrojet (GREENWALD *et al.*, 1975). However, when the spike develops, with the maximum velocity increasing with time, the H perturbation decreases and goes negative, the reverse of what would be expected. This indicates that the eastward jet has become very weak and that the westward jet is penetrating into the evening sector on its poleward side. The weakening of the easterly jet is consistent with the weakening and disappearance of diffuse auroral echoes, and their relatively small doppler shift. However, the doppler velocity remains positive out to the radar horizon, indicating that the westward electrojet, which would produce a negative doppler, must be at a higher invariant latitude than 65.7°. The negative excursions in D in Fig. 6 indicate upward field-aligned currents associated with the westward jet.

These results are typical, the magnetic effects of drift spikes are difficult or impossible to detect. In general the maximum spike velocity tends to occur at a time near the maximum depression in H, and echoes characteristic of the westward jet or Harang discontinuity often do not appear within the radar horizon, which may be up to 7° poleward of the spike. This is consistent with the published satellite observations, where small ion drifts are observed over several degrees of latitude poleward of the spike. The high latitude of the westward electrojet is borne out by examination of magnetograms from Macquarie Island (L=5.4); in all cases the Z component indicated the jet was poleward of the station.

These results indicate that the E-region ionization density in the spike must be very low. This is confirmed by examination of ionograms from Campbell Island, which show the electron density in the spike to be less than 10^{10} m^{-3}, the minimum observable on the ionosonde. If we neglect the motion of the ions a simple order of magnitude calculation shows that the effect of a drift spike with this electron density, 50 km half-width, and with Hall drift velocity along the L shell of 3 km s^{-1}, is less than 6 nT in H, which is small compared with the observed perturbations.

An indication of the relation of drift spikes to the precipitation that would be expected to be associated with the eastward electrojet may be gathered from a comparison of the auroral radar records with Campbell Island ionograms. Figs. 7 and 8 show such comparisons for the same two drift spikes illustrated previously. In both cases the spikes move equatorward over the ionosonde.

In Fig. 7 at 0730 UT diffuse echoes are over Campbell Island and a strong night-E layer is present. At 0800 UT the drift spike is starting to form, centred about 30 km south of the ionosonde, and there is only a very weak echo near 200 km on the ionogram. This echo can be interpreted partly as an oblique echo, and partly as additional ionization in the lower F region. At 0830 UT the drift spike is centred about 50 km equatorward of Campbell Island and an overhead night-E layer is present (note the beginning of retardation at the lower limit of the

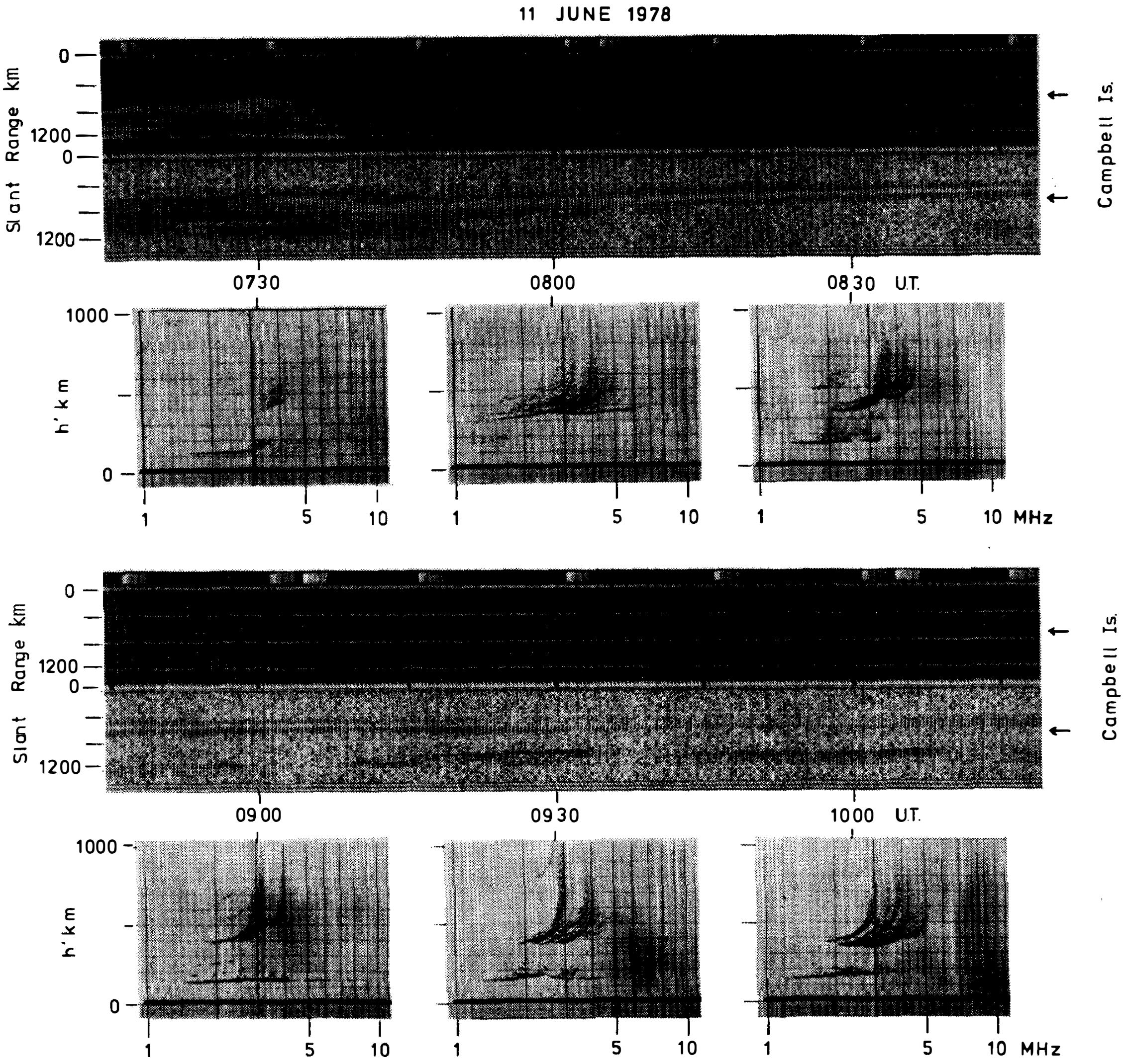

Fig. 7. Radar record and Campbell Island ionograms, 11 June 1978.

overhead F trace). As the drift spike moves further equatorward the night-E layer appears at lower altitude (130 km at 0900 UT) and then tends to decay as the drift spike decays.

Fig. 8 shows a particularly clear sequence. At 0700 UT the spike has not yet formed and there are oblique echoes at 160 km on the ionogram probably associated with the patch of diffuse radar echoes beyond 750 km range. At 0730 UT the spike is centred almost directly over the ionosonde and again there are only oblique echoes below the F region. At 0800 and 0830 UT, as the drift spike moves equatorward, an overhead night-E layer appears at progressively lower heights, down to 110 km at 0830 UT in this case. At 0900 UT the drift spike is rapidly decaying and the night-E layer is still overhead but at a height of 150 km.

We interpret these observations as indicating that the drift spike occurs just equatorward of any precipitation detectable as night-E on an ionogram. At its equatorward edge the precipitation is very soft and becomes harder with increasing distance poleward from the spike. The precipitation decays as the drift spike decays. The very little all-sky camera data we have from Campbell Island supports this interpretation, diffuse aurora appears well poleward of a drift spike and discrete aurora even more so.

This interpretation is in accord with the findings of WINNINGHAM *et al.* (1979) in their study of the auroral electrojets and precipitation regions. Their Table 1

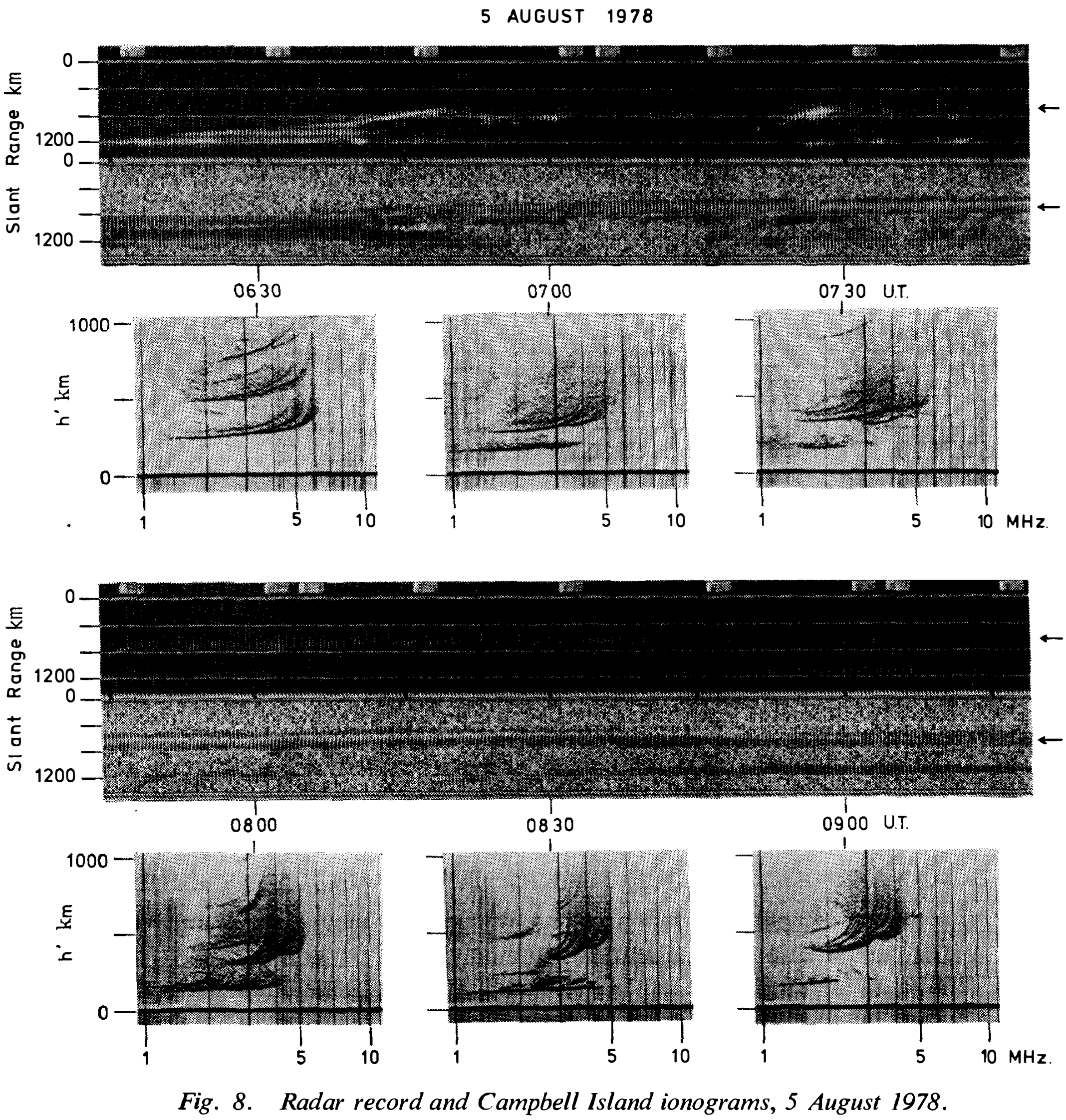

Fig. 8. Radar record and Campbell Island ionograms, 5 August 1978.

and Fig. 4 indicate that there is a pronounced softening of precipitation on the equatorward edge of the eastward auroral electrojet, the boundaries of >100 eV and >1 keV precipitation being separated by up to three degrees of latitude. Our findings suggest this gradient in energy persists as the drift spike develops and eastward electrojet decays.

It should also be noted from Figs. 7 and 8 that the precipitation poleward of the drift spike is very patchy, indicated by the number of oblique *E*-region echoes. This is in marked contrast to the precipitation associated with a well established eastward electrojet and the corresponding night-*E* layer (0730 UT on 7 June and accompanying positive bay on the Campbell Island magnetometer). It should also be noted from Figs. 7 and 8 that the *F*-region poleward of the spike is more patchy and with a smaller peak electron density than that equatorward, which is relatively smooth.

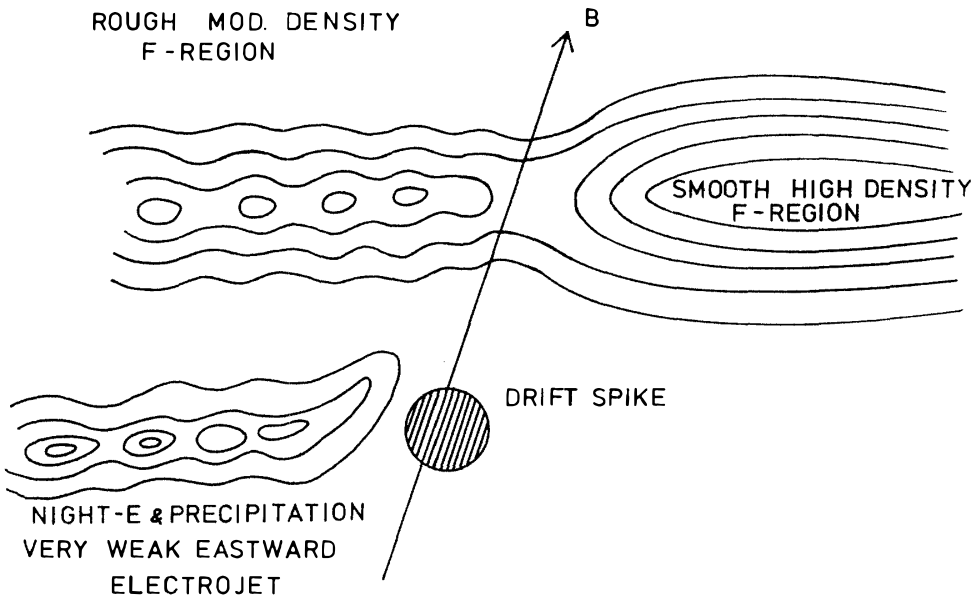

Fig. 9. Suggested meridional cross section of ionosphere in the neighbourhood of a drift spike in the Southern Hemisphere. Poleward to the left.

In Fig. 9 we suggest a model ionosphere that is consistent with the present evidence, with the drift spike situated in the trough at the equatorward edge of a very weak eastward electrojet in which the electric field is very small and precipitation variable. The model is consistent with the spatial gradient in the energy of precipitating electrons (WINNINGHAM *et al.*, 1979), and can be supported by ray tracing arguments.

4. Summary and Conclusions

In summary, drift spikes appear following substorms when the ionosphere is in darkness. They occur in the trough just equatorward of the low latitude edge of precipitation associated with the eastward electrojet, though the electrojet itself decays as the spike develops. During its lifetime, which may be up to two hours, the spike migrates equatorward in an irregular manner possibly reflecting the behaviour, though less dramatically, of the westward jet penetrating eastward at higher latitude, or expansion of the auroral oval. The behaviour of the spike suggests a possible squeezing of the sunward convective flow against the plasmasphere. The maximum peak velocity in the spike may be associated with maximum penetration of the westward electrojet.

The magnetic effect of a drift spike is difficult or impossible to detect at the ground, even if the magnetometer is situated directly below the spike. It follows that the ionospheric conductivity must be very low in its immediate neighbourhood, which gives support to BANKS and YASUHARA's (1978) model calculations of the latitudinal distribution of ionization in the presence of the poleward-directed electric field associated with the spike. It is not yet clear why some substorms are followed by drift spikes, and other apparently closely similar are not. Nor is it clear why the convection electric field appears to be concentrated over such a small interval equatorward of a wide interval that itself is wholly equatorward of the westward jet. However, we are dealing with a transient phenomenon in the whole magnetosphere/ionosphere system and more observations, including data from a network of ground-based stations and satellite data to provide information on precipitation and field-aligned currents, are required to answer these questions.

In conclusion it should be mentioned that other auroral radars with doppler capability (STARE, Homer, Anchorage) all probe the ionosphere at L values greater than five, where drift spikes have so far not been observed (Fig. 5). It is hoped that this situation can be rectified in future in an area where an accompanying network of ground stations can be established.

Acknowledgements

The Slope Point auroral radar was operated by J. KEYS, P. JOHNSTON and B. McNAMARA of the PEL Auroral Station, and the instruments on Campbell Island by staff of the New Zealand Ministry of Transport. Copies of Macquarie Island magnetograms were kindly supplied by the Director of the Bureau of Mineral Resources, Australia.

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(*Received March 31, 1980*)