THE IONOSPHERIC SIGNATURE OF THE POLAR CLEFT OVER HALLEY, ANTARCTICA

A. S. RODGER *and* S. M. BROOM

British Antarctic Survey, Natural Environment Research Council, Madingley Road, Cambridge, CB3 0ET, UK

ABSTRACT. Ionosonde data from Halley, Antarctica (76°, 27° W; $L = 4.2$) are used to investigate the rare signature of the polar cleft in the E and F regions of the ionosphere. The cleft is only observed over Halley during very disturbed geomagnetic conditions; we have identified only five occurrences in a ten-year period. The major features are a fourfold increase in the maximum plasma frequency of the F layer, the presence of many irregularities throughout the F layer and a small enhancement of E-region maximum plasma frequencies. The cleft's ionospheric signature in winter is very similar to that observed at higher geomagnetic latitudes during moderate and quiet geomagnetic conditions. However, in summer the Halley ionograms show the presence of an $F1$ layer where those from higher latitudes do not. Some possible explanations are discussed.

The geophysical conditions under which the cleft is observed at Halley are described using the AE and Dst indices, together with some interplanetary magnetic field data. The moduli of AE, Dst and B_z are all large for the events studied. The y-component of the interplanetary magnetic field appears to have no significant effect upon the time when the cleft is observed. A comparison of the geomagnetic latitude of the observed cleft signatures with the predictions of empirical models based upon solar-wind data and geomagnetic indices shows that the latter underestimate the equatorward excursion of the cleft under very disturbed conditions. A revision of these formulae is therefore necessary.

INTRODUCTION

The entry of plasma of solar-wind origin through the polar cusp plays a major role in determining the structure and dynamics of the high-latitude ionized atmosphere; its importance was recognized over 50 years ago (Chapman and Ferraro, 1931). The regions where the effects of the solar-wind plasma are observed in the ionosphere and magnetosphere can be very extended. Recently there had been some desire to separate this region into two, termed the cusp and the cleft (Heikkila, 1985; Hardy and others, 1985). The cleft is considered to be the low-altitude region around noon where there is significant precipitation of electrons of energies ~ 100 eV and associated enhancements of the 630 nm emission. The cleft also contains structured electron precipitation of higher energies. The cusp is a more localized region near noon, within the cleft, characterized by low-energy precipitation only, having no discrete auroral arc but often displaying irregular behaviour. However, these definitions cannot be applied rigorously. Thus in this paper we will not attempt to differentiate between these two regions, but will use the term cleft throughout.

There has been, and continues to be, very extensive study of the cleft's position, properties and effects on the ionosphere and thermosphere by means of a wide variety of techniques (e.g. Clauer and others, 1984; Holtet and Egeland, 1985). The majority of the studies of the cleft and the various effects of the large fluxes of precipitating electrons have been made using satellite data or ground-based instruments at stations near the latitude of the cleft under quiet or moderately disturbed geomagnetic conditions ($\Lambda \sim 75°$) (e.g. Whitteker, 1976; Eather and others, 1979; Eather, 1984, 1985;

Meng, 1984; Jorgensen and others, 1984). Little attention has been paid to the possibility of studying the cleft at comparatively low invariant latitudes ($\Lambda \sim 60°$) during periods of intense geomagnetic activity.

The purpose of this paper is to describe the ionospheric signature of the polar cleft recorded by the ionosonde at Halley, Antarctica (76°, 27° W, $\Lambda \sim 60.8°$) and to compare this signature with those from higher invariant latitudes. In winter, we find that there is no significant difference between the ionogram signatures of the cleft over Halley under very disturbed geomagnetic conditions. However, in summer an *F1* layer is present at Halley when the cleft is overhead, whereas it is not present at higher geomagnetic latitudes. Possible interpretations of this difference are discussed. We investigate the geophysical conditions under which the cleft is observed at Halley by using the AE and Dst indices and the southward component of the interplanetary magnetic field (B_z). We also compare predictions of existing empirical formulae for the geomagnetic latitude of the cleft that use AE, Dst and B_z values with our Halley observations. We find that these equations consistently place the cleft at geomagnetic latitudes higher than that of Halley. We comment on the significance of our findings regarding both the processes involved in controlling the dynamics of the cleft and the requirement for a revision of the empirical formulae to take account of our results.

Ionogram Signatures of the Cleft in Winter and Summer

The frequency plot (f-plot) data from Halley for the ten years from January 1973 have been examined to determine occasions when the polar cleft was observed in the vicinity of the station. The most obvious characteristic of the cleft on an f-plot is a very large increase (in excess of 2 MHz) in the maximum plasma frequency of the *F* region within ± 3 h of magnetic noon ($\sim$ 1200 UT $\pm$ 3.5 h); the increase lasts for about 3 h. An example is given in Fig. 1, which shows the variations of the maximum plasma frequency of the *F* region (*foF2*) for 15 September 1974 as a function of local time. The symbols used are consistent with the internationally agreed rules (Piggott and Rawer, 1972). There is a very significant and rapid increase in *foF2* at 1245 LT ($\sim$ 1115 MLT) from 5.2 MHz to 10.3 MHz at 1500 LT. This is equivalent to an increase in electron concentration by a factor of four. The observed values of *foF2* are very significantly above the median and upper quartile values for the month, shown by the full and broken lines respectively in Fig. 1. These observations can be regarded as typical of other occasions when the ionospheric signature of the cleft is seen from Halley.

Selected ionograms from a sequence recorded by the Advanced Ionospheric Sounder (AIS) deployed at Halley (Dudeney, 1981) are shown in Fig. 2 for 25 July 1981 – a winter day on which the cleft was observed over Halley. Before 1300 LT, the *foF2* values are $\sim$ 6 MHz, similar to the median values for the month before rising rapidly to reach a maximum value for *foF2* of 12.8 MHz. From 1330 LT to 1500 LT, the *foF2* values are considerably in excess of the monthly median values. Also there is a very marked increase in the amount of range and frequency spread-*F* (Piggott and Rawer, 1978) on the *F*-region traces. Spread-*F* on ionograms arises from the presence of medium-scale irregularities ($\sim$ 1–10 km) in electron concentration, and such features are frequently though not invariably associated with the cleft. From 1545 LT, the *F*-region electron concentration returns to approximately the same value as that prior to the observation of the cleft. The virtual height of the *F* region falls to a minimum value of 210 km at 1430 LT, when the direction-finding capability of the AIS shows that the *F* layer is overhead.

There is an enhancement in the maximum plasma frequency of the *E* region

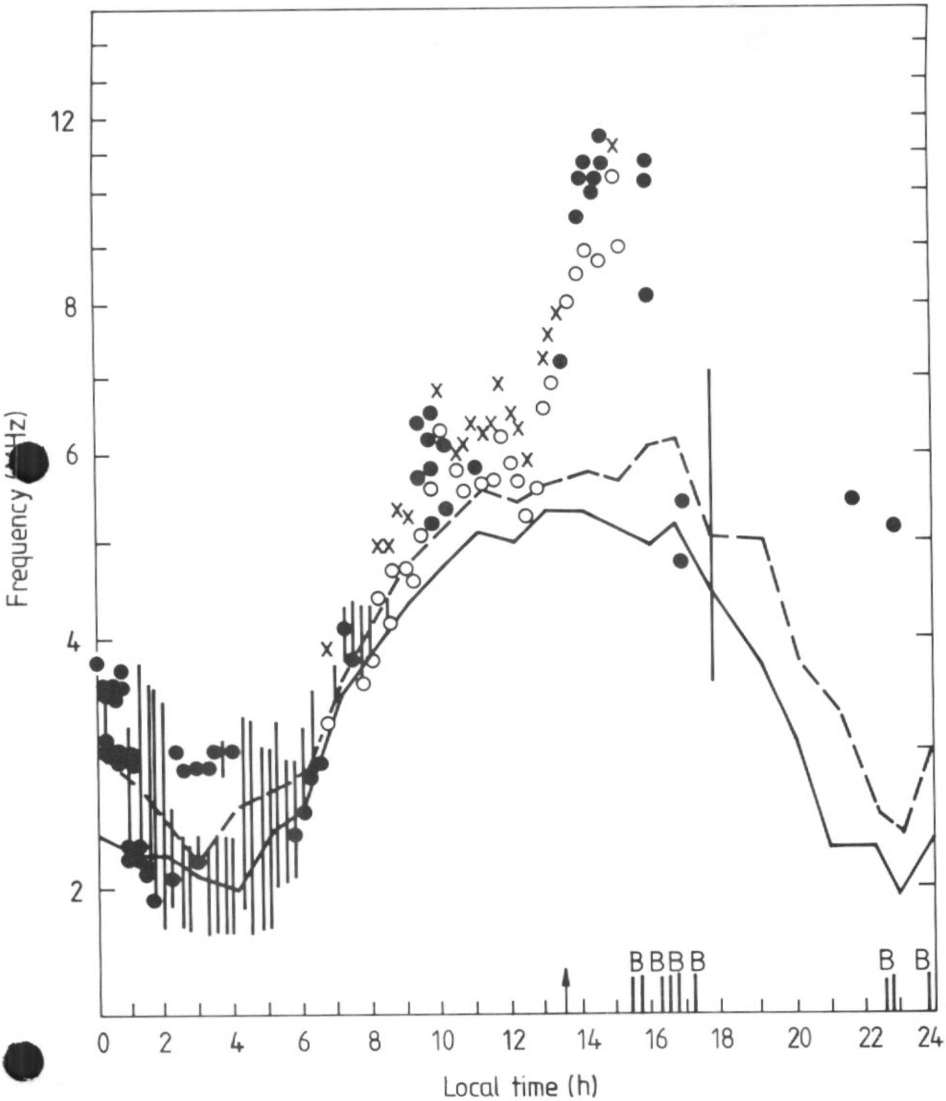

Fig. 1. A frequency plot of *F*-region parameters for 15 September 1974 from Halley showing one signature of the polar cleft between 1300 and 1600 LT. The symbols used are consistent with those internationally agreed (Piggott and Rawer, 1972). The monthly median and upper quartile values for September 1974 are shown by the full and broken lines respectively. The small vertical lines on the local time axis show the occasions when no echo was recorded due to very high radio-wave absorption (blackout, B). The vertical arrow indicates local magnetic noon.

indicated by the presence of particle-*E* (Piggott, 1975). This shows that there is some energetic particle precipitation (electrons with energies in the range 1–10 keV). Both the *E*- and *F*-region observations are consistent with the ionogram signatures of the cleft observed in winter at higher invariant latitudes under less disturbed geomagnetic conditions (e.g. Stiles and others, 1979).

In summer, which is defined for our purposes as occasions when the *F1* layer is

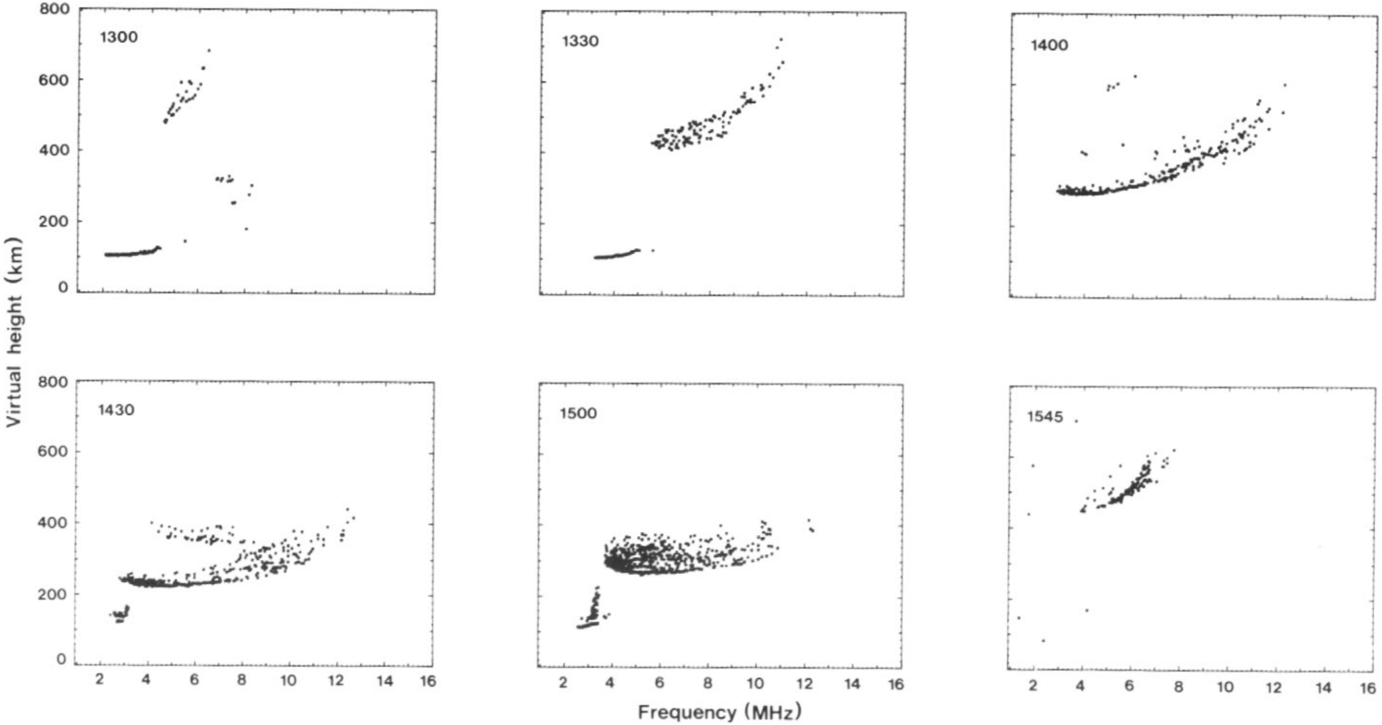

Fig. 2. Selected ionograms from a sequence recorded by the AIS on 25 July 1981 when the cleft was in the vicinity of Halley. The local time for each ionogram is shown in the top left corner. The main characteristics of the cleft are a very large increase in *foF2* and the presence of significant range and frequency spread on the *F*-region traces. Some enhancement in the *E*-region densities is also noted.

observed, the appearance of the *F2* layer associated with the cleft is rather similar to that observed in winter. Selected ionograms from a summer observation of the cleft for 26 September 1982 are shown in Fig. 3. The *foF2* values increase dramatically from 1230 LT and the *F* region exhibits both range and frequency spread-*F*. There are many similarities between the *F2*-region traces on the ionograms between 1300 and 1500 LT in Fig. 3 with those at 1400 and 1500 LT in Fig. 2, except that the former show that an *F1*-layer is present at 1400 LT when the direction-finding capability of the AIS shows that the cleft-associated layer is overhead. By 1500 LT, the cleft layer has become screened by a particle-*E* layer but, because the virtual height of the *F2* layer is unaltered, it is reasonable to assume that the *F*-layer N(h) profile has not changed substantially. Ionogram sequences from stations at higher magnetic latitudes, such as Cape Parry, Sachs Harbour, Vostok and Pole Station (Dudeney and Piggott, 1978; Hoeg and Ungstrup, 1983; Besprozvannaya and Shchuka, 1984) show that the virtual height of the *F* layer falls to about 200 km, and any indication of the *F1* layer disappears completely. Thus our ionogram signature of the cleft made from Halley during summer conditions is in contrast to those higher magnetic latitudes.

For all observations of the cleft, irrespective of the invariant latitude at which they are made, the *E*-region maximum plasma concentration does appear to show some increase, normally by about a factor of two.

We have positively identified the cleft in the vicinity of Halley on five occasions from January 1973 to December 1982. The dates of these events are 15 September 1974, 29 August 1979, 19 December 1980, 25 July 1981 and 26 September 1982. The ionogram signatures illustrated in Figs. 2 and 3 can be regarded as being typical for winter and summer respectively. The geophysical conditions under which these observations were made are discussed in the next section.

Geophysical Conditions when the Cleft Signature is Observed Near Halley

We have investigated the geophysical conditions under which the ionospheric signature of the cleft is observed at Halley for each of the five occasions listed in the previous section by using the hourly equatorial Dst index (see Mayaud, 1980), the hourly Auroral Electrojet index, AE (Davis and Sugiura, 1966) and some interplanetary magnetic field data. The variations of *foF2*, Dst and AE through each event are illustrated in Fig. 4. The time of the maximum *foF2* values and local magnetic noon are indicated by downward and upward arrows respectively. The maximum value of *foF2* exceeds 12 MHz for four of the events. On the other occasion, 19 December 1980, *foF2* showed only a comparatively small increase in *foF2* (*foF2* ~9.0 MHz) but more comprehensive ionospheric data from Siple station (Rosenberg and others, 1983) leave us in no doubt that the cleft was in the vicinity of Halley on this day. Often, the *F* layer was obscured before or after the cleft signature was observed. At these times, Halley was under the influence of the morning and afternoon auroral ovals, where there are very significance fluxes of energetic particles precipitating into the *D* region (Potemra and Zanetti, 1985; Burch and Reiff, 1985) causing greatly increased radio wave absorption, especially under disturbed geomagnetic conditions (Hartz and Brice, 1967; Rodger and others, 1981; Hargreaves and others, 1985).

For each occasion, the Dst index has become quite disturbed (Dst ~100 nT) and, in general, the Dst reaches its maximum negative excursion some hours after the cleft is observed at Halley. Meng (1984) concluded from an analysis of DMSP satellite data that the maximum equatorward excursion of the cleft occurred about 2–3 h prior to the minimum value of Dst. Our results tend to support this hypothesis,

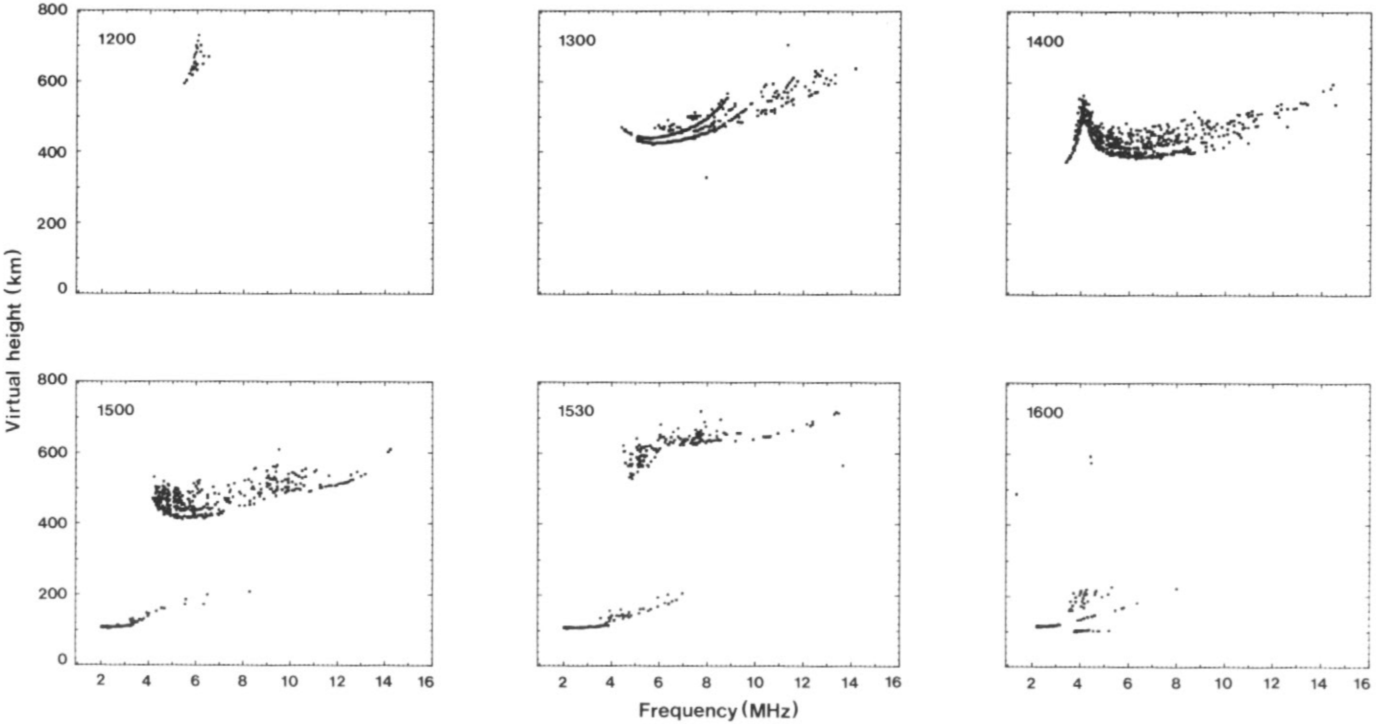

Fig. 3. Selected ionograms from a sequence recorded by the AIS on 26 September 1982 when the cleft was observed in the vicinity of Halley. The local time for each ionogram is shown in the top left corner. The 1600 LT ionogram showed the presence of slant *Es*, a characteristic of the day-time auroral oval (Sylvain and others, 1978), which is often observed after cleft events.

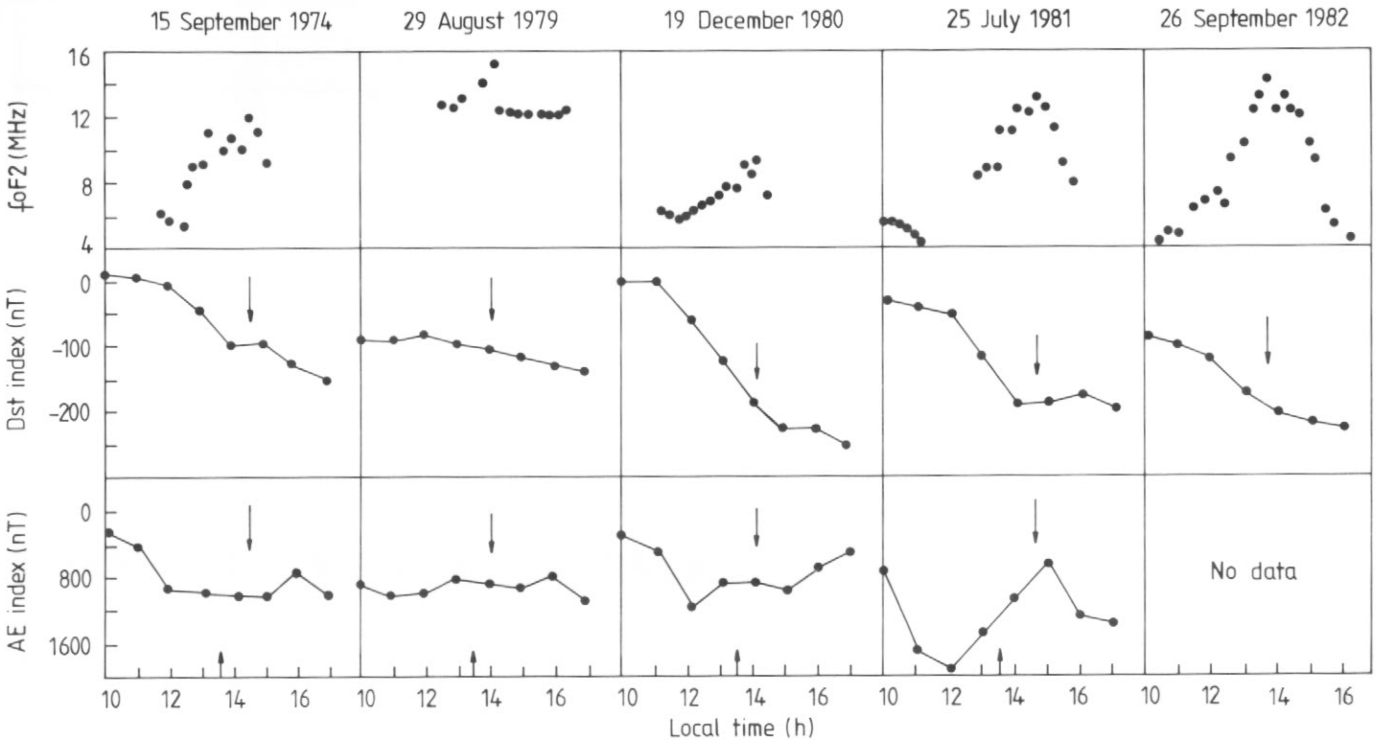

Fig. 4. The local time variations of *foF2* (top panels) for each of the five occasions that the cleft has been identified from Halley in the ten-year period from January 1973 together with the hourly values of the Dst and AE indices (middle and bottom panels respectively). Downward arrows give the time of maximum *foF2* values. Upward arrows indicate local magnetic noon.

although they are limited in their description of the spatial and temporal evolution of the cleft because they come from a single station.

The AE index shows no consistent behaviour for the four occasions that it was available, though clearly the ionosphere was very disturbed as AE exceeded 750 nT at the time when the maximum *foF2* values were recorded at Halley (Fig. 4).

B_z was found to be very negative for each of the three occasions for which IMF data were available. At the time of maximum *foF2*, B_z was approximately -10 nT on 29 August 1979, -29 nT on 19 December 1980 and -20 nT on 26 September 1982. These observations are consistent with previous studies (e.g. Meng and Candidi, 1985), which suggest that B_z must be large and negative for significant equatorward excursions of the cleft position to occur. For these three examples, B_y was 0, $+6$ and $+10$ nT respectively. As the time of maximum *foF2* appears to be virtually the same for each example (1400 LT $\pm$ 20 min), our data suggest that the time when the cleft is observed is not significantly affected by B_y. This result is consistent with the observations of Rodger and Cowley (1986) and Burch and others (1985). Heelis (1982, 1984) has also shown that the day-side throat in the ion convection pattern does not move appreciably in magnetic local time as a function of B_y. However, Meng and Candidi (1985) suggest that the area into which precipitation occurs does depend upon the magnitude and direction of B_y. Further study of the influence of B_y on cleft processes is required.

Discussion

The ionogram signature of the cleft in winter appears to be the same at high and comparatively low geomagnetic latitudes, and this is independent of the level of geomagnetic disturbance. We have examined some spectra of precipitating electrons measured by satellites (Gussenhoven and others, 1985; Burch and Reiff, 1985) in addition to studying spectra from the Dynamics Explorer-2 Low Altitude Plasma Instrument (Winningham and others, 1981). We find that the energy spectra of precipitating electrons appears to be independent of the level of geomagnetic activity. The maximum flux of electrons occurs at energies of ~ 250 eV, with a maximum energy of ~ 1 keV (see references for further details). (Electrons with these energies will deposit the majority of their energy at about 240 and 150 km respectively (Rees, 1963).) Thus the similarity of the ionograms from high magnetic latitudes under quiet and moderate geomagnetic conditions to those from the comparatively low-latitude observatory at Halley under very disturbed conditions is to be expected. It has been found that the flux of precipitating particles depends mainly upon the solar-wind density and the magnitude of the southward component of the interplanetary magnetic field, B_z (Meng and Candidi, 1985), but we do not have a sufficiently large data sample with the corresponding solar-wind data to comment on this point.

In summer there is a significant difference in the ionogram signature of the cleft, in that an *F1* layer is present throughout cleft observations at Halley's latitude but is absent when the cleft is overhead at higher magnetic latitudes. The occurrence of an *F1* layer is dependent upon the height (ht) at which the recombination changes from an α- to a β-dominated regime, and upon the height of maximum electron–ion pair production (hm). If ht > hm, then an *F1* layer is observed. Rishbeth and Garriett (1969) and Torr and others (1979) give a more complete description of the cause of the *F1* layer and the various recombination processes involved. Rishbeth and Garriott also show that the shape of the distribution of ionization in the vicinity of *hmF1* depends upon $\beta^2/(\alpha q)$, when q is the ion–electron pair production rate. The energy spectra of precipitating particles in the cleft region as described above should explain the significant rise of hm, which causes the *F1* layer to disappear in summer at all latitudes when the cleft is overhead. However, the thermospheric composition and temperature also vary as a function of latitude and geomagnetic conditions (Hedin, 1983 and the references therein); thus ht will be strongly latitude- and activity-dependent. Further, local Joule heating by high-latitude Hall currents (Feldstein, 1976), frictional heating through ion–neutral collisions (Killean and others, 1984) and particle precipitation will all conspire to change the temperature and composition of the thermosphere at the foot of the cleft flux tube. Thus it is not possible to identify precisely which mechanism is responsible for the difference in the *F1*-layer behaviour described above without very careful modelling work, which is beyond the scope of the present paper.

Eather (1985) carried out a detailed analysis to determine the parameters with which he could predict most accurately the geomagnetic latitude of the cleft. He used a multiple linear regression method with the parameters B_z, the solar-wind pressure P, and the indices AU, AL, AE and Dst. He found that the combination of P, AE and Dst predicted most accurately the latitude of the cleft. We have used his equations for linear regression determined using B_z, AE and Dst separately, and his multiple linear regression result for AE and Dst combined, to predict the geomagnetic latitude of the cleft for the events seen at Halley for which interplanetary magnetic field data were available. We have used the values of AE, Dst and B_z closest to the time when Halley observed the maximum *foF2* (downward arrows on Fig. 4). The average latitude of the cleft for all events, together with the equations used, are given in Table I. It shows that B_z and the AE index give the best prediction for the cleft position

Table I. Predicted geomagnetic latitude of the cleft.

Index	*Equation (after Eather, 1985)*	*Sample size*	*Average predicted latitude*
AE	$-0.011\text{AE}+76.7°$	4	66.6°
Dst	$0.047\text{Dst}+74.5°$	5	68.5°
B_z	$0.318B_z+72.7°$	3	66.5°
AE + Dst	$0.005\text{Dst}\pm0.010\text{AE}+77.4°$	4	67.4°

($\Lambda \sim 66.5°$), though the data-sets are small. Each empirical equation gives an average geomagnetic latitude of the cleft higher than that of Halley (whose geomagnetic latitude is 65.8°) by between 0.7° and 2.7°, even allowing for the quoted errors in Eather's equations.

There has been considerable discussion in the literature over the processes that limit the equatorward excursion of the cleft during geomagnetic activity. Some authors (e.g. Meng, 1984; Sandholt and others, 1983) favour mechanisms controlled by processes external to the magnetosphere, involving the solar wind and interplanetary magnetic field; Akasofu and others (1981) suggest that the equatorward motion of the cleft is the result of an enhanced dynamo current in the day-side boundary layer, whereas Eather (1984) suggests that the internal magnetospheric effects are more important. These include the build-up of the equatorial ring current, which can be quantified by the Dst index, and magnetospheric tail currents, which are related to the AE index. Our data cannot be used to verify either opinion, but both AE and B_z give better results than other relations studied by this paper. This suggests that both external and internal magnetospheric influences are important.

Our observations of the ionospheric signature of the cleft are made close to the maximum equatorward excursion of the cleft flux tube and are further equatorward than the predictions of the empirical models of Eather (1985). Thus our data need to be taken into account in any revision of these empirical formulae.

Conclusions

1. We have illustrated typical ionogram and frequency plot signatures of the polar cleft at comparatively low geomagnetic latitudes using data from Halley, Antarctica.

2. The ionogram signature of the cleft in winter observed at Halley during very high geomagnetic activity is very similar to that observed at higher geomagnetic latitudes under moderately disturbed and quiet geomagnetic conditions.

3. In summer, the ionogram signature of the cleft at Halley shows the presence of an *F1* layer while that from higher geomagnetic latitudes does not. Some possible explanations have been discussed, but modelling work is required.

4. A study of the geophysical conditions under which the cleft has been observed at Halley on five occasions in a ten-year period have been described. The modulus of AE, Dst and B_z is large for all examples. B_y has no discernible effect on the local time when the cleft is observed.

5. Predictions made using the empirical formulae of Eather (1985) for the geomagnetic latitude of the cleft all underestimate the equatorward excursion for each of the five occasions presented here. Our observations suggest that a revision of the empirical formulae is required.

Acknowledgement

We are grateful to Mr M. Pinnock of British Antarctic Survey for some helpful discussions and comments on the script.

Received 11 October 1985; accepted 18 February 1986

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