# SPORADIC *E* (*Es*) ASSOCIATED WITH THE MAIN IONOSPHERIC TROUGH OBSERVED OVER HALLEY STATION, ANTARCTICA

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ABSTRACT. The occurrence of sporadic *E* (*Es*) under the main ionospheric trough is investigated using vertical incidence ionosonde data from Halley station, Antarctica (76° S, 27° W; $L = 4.2$). This is an ideal location for such studies as the trough is seen over a wide range of magnetic conditions and local times. The study reveals that, before magnetic midnight, *Es* layers with semi-thickness similar to that of the normal day-time *E* layer are observed most frequently whereas, after midnight, the *Es* layers are usually much thinner. It is argued that the source of the additional ionization in the *E* region is most likely to be proton precipitation before magnetic midnight but electron precipitation thereafter. A simple method is used to estimate the fluxes and energies of the precipitating charged particles necessary to produce the observed *Es* layers. It is suggested that the observed change in the *Es*-layer thickness about midnight is related to the difference in the type and energy spectrum of the precipitating particles. The effects of transport processes in the *E* region are briefly considered but no conclusions drawn concerning them; it is suggested that redistribution of ionization by the convection (dawn–dusk) electric field may be important during disturbed conditions.

## INTRODUCTION

Since the establishment of the ionospheric observatory at Halley, Antarctica (76° S, 27° W), during the International Geophysical Year, records have consistently contained sequences of ionograms that are characteristic of movements of an ionization depletion in the night-time *F* region. Originally designated 'Replacement-layer Sequences' by Bellchambers and others (1962), these have since been identified as movements of the mid-latitude, or main, ionospheric trough (Muldrew, 1965; Sharp, 1966; Lockwood, 1981). Many investigations concerning the formation and morphology of the trough have been carried out (Banks and others, 1974; Knudsen, 1974; Schunk and others, 1975, 1976; Spiro and others, 1978), and a comprehensive review of the subject has been published by Moffett and Quegan (1983). A schematic diagram of the trough (Fig. 1) shows that it comprises three regions: an equatorial edge, a poleward edge and the trough minimum. Both electron concentration and its gradient at the equatorial edge are highly variable, and the region is thought to be an extension of the mid-latitude ionosphere (Dudeney and Piggott, 1978). The poleward edge is a region of enhanced particle precipitation (Pike and others, 1977; Voss and Smith, 1980) and is usually regarded as the equatorial boundary of the oval (Liszka and Turunen, 1970). The possible effects of this precipitation on the *E* region do not appear to have been investigated specifically. Bellchambers and others (1962) found that the details of replacement-layer sequences were often obscured by blackout and auroral *Es* during magnetically disturbed conditions. Also, Bowman (1969) noted that *Es* consistently appeared with the onset of trough crossings over Ellsworth, Antarctica. More recently, Rodger and others (1983) have provided descriptions of *Es* associated with the

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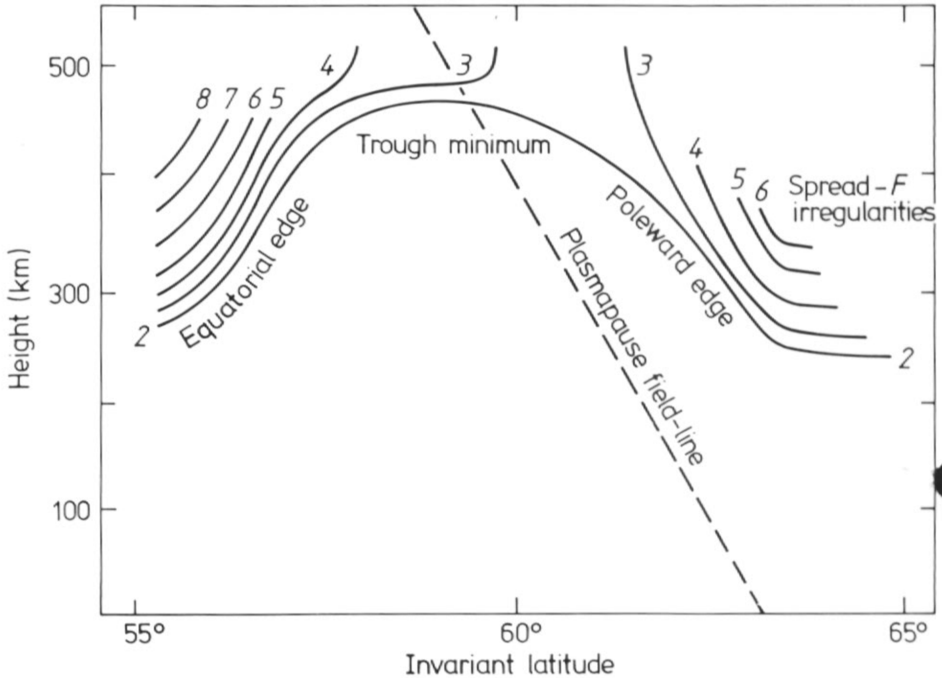


Fig. 1. Schematic diagram of the mid-latitude ionospheric trough. The numbers associated with the iso-ionic contours are plasma frequencies in MHz. The three regions of the trough are the equatorial edge, the trough minimum and the poleward edge. The magnetic field line through the statistical average position of the plasmapause is indicated by the dashed line.

trough as observed from Halley. The purpose of this report is to expand on these latter results, and to provide some further evidence in support of the conclusions based on them.

## THEORY

*The plasmapause and gyroresonance*

The trough is known to move equatorwards in the early evening hours and also with increasing geomagnetic activity (Rodger and Pinnock, 1980, 1982). Its mean position is near $L = 4$; consequently, it can be observed from Halley ($L = 4.2$) on most nights throughout the equinoctial months and the austral winter. Statistically, the plasmapause and the trough minimum lie on approximately the same geomagnetic field line (Rycroft and Burnell, 1970), although not necessarily for individual cases (Titheridge, 1976; Grebowsky and others, 1978). This allows the possibility of particles being precipitated by gyroresonance from the ring current. In this interaction, particles trapped on magnetic field lines lose transverse energy to electromagnetic waves at frequencies equal or close to their gyroresonance. Precipitation from gyroresonance increases greatly as cold plasma density increases, and particles crossing the plasmapause into the plasmasphere thus enter a region of increased precipitation probability. Enhanced precipitation is therefore expected in the vicinity of the plasmapause and hence in the vicinity of the trough. Cornwall and others (1970), Hultqvist (1975), Gendrin (1975) and Soraas and others (1977) have provided detailed descriptions of this process.

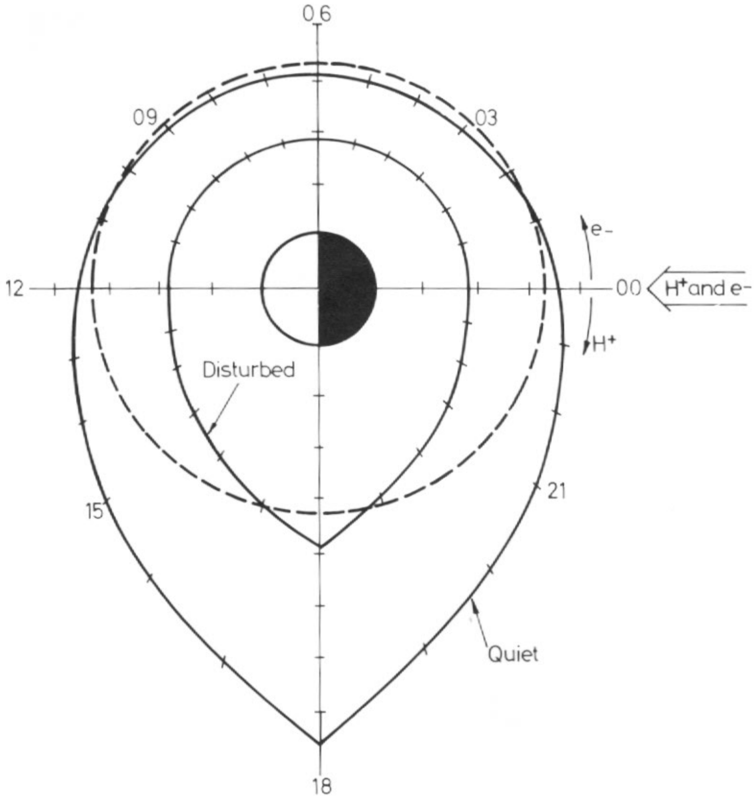


Fig. 2. The dashed line indicates the locus of Halley as a function of local time, projected into the equatorial plane. The radial axis is $L$-shell. The outer and inner continuous lines show the locus of the plasmapause for quiet ($Kp \simeq 0$–1) and disturbed ($Kp \simeq 5$) magnetic conditions determined from the model of Kavanagh and others (1968).

*Particle precipitation in the vicinity of Halley*

The position of the plasmapause is illustrated in Fig. 2 for high and low levels of geomagnetic activity, determined from the theoretical model of plasmapause position developed by Kavanagh and others (1968). In this model, the plasmapause is taken to be the last closed equipotential of the electric field resulting from the sum of the convection and corotation electric fields in a sun–earth coordinate frame of reference. The locus of the Halley field line in the equatorial plane is shown by a dashed line. Particles that are injected near midnight on to the $L$-shell of Halley ($L = 4.2$) will already have crossed the plasmapause when quiet geomagnetic conditions prevail ($1 < Kp < 2$). Consequently, many of the particles traversing the plasmapause will be precipitated some distance poleward of Halley and are not important in this study. For geomagnetically active conditions ($Kp \simeq 5$), charged particles injected to the $L = 4.2$ shell will drift azimuthally, with electrons drifting eastward to later local times and protons drifting westward to earlier local times. On such an occasion the protons will encounter the plasmapause near 1900 LT and enhanced proton precipitation would be expected near Halley. Therefore, in general, there is a range of geomagnetic conditions for which enhanced proton precipitation is expected in the vicinity of Halley in the evening sector.

Electrons drifting towards later local times on a given $L$-shell do not encounter the plasmapause in the local time sector 0000–0600 LT, as the plasmapause gradually moves to lower $L$-shells during this period. Electrons drifting azimuthally in the ring current can still be precipitated between 0000 and 0600 LT through a number of wave–particle interaction processes.

In this brief discussion several assumptions have been made which may not be realistic in practice. For example, the plasmapause model assumes a constant dawn–dusk electric field directed from 0600 to 1800 LT. However, this simple theory does show that proton precipitation should occur near Halley before local midnight during geomagnetically active conditions while electron precipitation is more likely to predominate in the time sector 0000–0600 for geomagnetically quieter conditions. This is confirmed by satellite data (e.g. Potemra, 1979; Voss and Smith, 1980).

*Ionization caused by charged particle precipitation in the E-region*

Detailed theories of ionization produced by particle precipitation have been presented by several authors (Rees, 1963, 1975; Bennet and Noel, 1965; Edgar and others, 1975; Karzenbaum and Gagliardini, 1981; Gagliardini and Karzenbaum, 1982). Accurate computations of ionization production profiles require complicated integrations over the energy spectra and pitch angle distributions of the incoming particles. In addition, allowances must be made for the differing ionization cross-sections of each of the neutral species along the path. Several such profiles have been computed by Rees (1963) and Edgar and others (1975) for constant fluxes of mono-energetic particles with isotropic pitch angle distributions. These show that high energy particles produce denser layers of ionization at lower altitudes, and over a smaller height range, than low energy particles.

For the purpose of this study it will be sufficient to obtain order-of-magnitude estimates of the particle fluxes required to produce the observed *Es* layers, so that a very elementary method may be used. It is assumed that the total energy of the precipitated particles is deposited uniformly in a horizontal slab of thickness $d$, and that the energy required to produce an ion-electron pair within the slab is $\eta$. It is further assumed that the particle stream is mono-energetic, each particle possessing energy $\varepsilon$, and that all of this energy is used to produce ionization. This last assumption is admittedly unrealistic, but the results of Rees (1975) indicate that well over half of this energy is used in ionization. The result of the assumption is that particle fluxes will be overestimated; however, the overestimation is by a factor of less than two, so that the flux estimates should still be correct to an order of magnitude. For a particle flux of $\phi$ the ion pair production rate, $q$, will be given by

$$q = \frac{\varepsilon\phi}{\eta d}$$

The layer produced is assumed to be in chemical equilibrium, with transport and diffusion negligible, so that the continuity equation reduces to

$$q = \alpha N^2$$

where $\alpha$ is the recombination coefficient and $N$ is the electron concentration. This may be obtained from the maximum plasma frequency of the *Es* layer, here identified with *foEs*, using the well-known formula (Piggott and Rawer, 1978)

$$N = 1.24 \times 10^{10}\ (foEs)^2\ \mathrm{m}^{-3}$$

where *foEs* is expressed in MHz. Using the above relations, the particle energy and

Table I. A summary of the features of the mid-latitude trough types identified by Rodger and Pinnock (1980).

| | *Type 1* | *Type 2* | *Type 3* | *Type 4* | *Type 5* |
|---|---|---|---|---|---|
| Time of occurrence (local time) | 1600–2000 | 2000–2300 | 2300–0100 | 0100–0500 | Usually after 0100 |
| Magnetic activity (*Kp*) | >5 | 3–5 | 3–5 | 2 | <2 |
| Time to cross Halley (hours) | 2 | 3 | 3 | 4 | Does not cross |
| Conditions following trough | Blackout, high latitude ridges, very disturbed | Similar to 1 but less severe | Very extensive spread-*F*; blackout rare | Extensive spread-*F* | Sunrise ends sequence |

fluxes required to form observed *Es* layers can be roughly estimated. The value of $\alpha$ is taken to be $3 \times 10^{-7}\,cm^{-2}\,s^{-1}$ (Whitehead, 1970), and $\eta = 35$ eV.

## Data Analysis and Results

Observations of the mid-latitude trough from Halley (Rodger and Pinnock, 1980) have shown that trough events can be divided into five types, distinguished by the pattern of *E*- and *F*-region traces recorded on ionograms. Analysis revealed that an ordered set of conditions is associated with each type, which depends mainly upon the level of geomagnetic activity and the local time when the trough is observed. These conditions are summarized in Table I. The same categories have been used to group the events considered in this study. In four of these types (1–4), the trough is observed to pass over Halley, but in type 5 it remains poleward of the observatory throughout. Sample plots of the maximum plasma frequency of both *Es* and *F* layers for each of types 1, 2, 4 and 5 are illustrated in Figs. 3–6 respectively. The ionogram sequence of a type 3 crossing is very similar to that of a type 2, and they are here considered as a single type. The definitions of all parameters and *Es* types are in accordance with URSI rules. Each example of a trough crossing over Halley shows that there is a characteristic rise in virtual height, $h'F$, of the equatorward edge, followed by a fall in $h'F$ as the poleward edge moves overhead. Usually there is a corresponding fall in the maximum plasma frequency of the equatorial edge, *foF2*, with a significant rise in *foF2* when the poleward edge is seen.

It is found that four types of *Es* are observed, namely auroral (*Es-a*), retardation (*Es-r*), flat (*Es-f*) and particle *E* (*Es-k*). Identification of each type is mainly by the appearance of the *Es* trace on the ionogram and line drawings of the relevant types are shown in Fig. 7. The distribution of electron concentration with height is different for each *Es* type, and their most important characteristics are summarized in Table II. It can be seen that *Es-a* and *Es-r* differ only in respect of the number of irregularities within the *Es* layer. Therefore, in the statistical analyses of this study the two types have been grouped together as *Es-r*. The sample sequences show that *Es* is frequently present under the trough, but initial observations suggest that there is less consistency than is seen with *F*-region features. The virtual heights of *Es-r* and *Es-k* often fall as the event proceeds and the selected examples show this behaviour more clearly than most. This can result from either vertical or horizontal movement

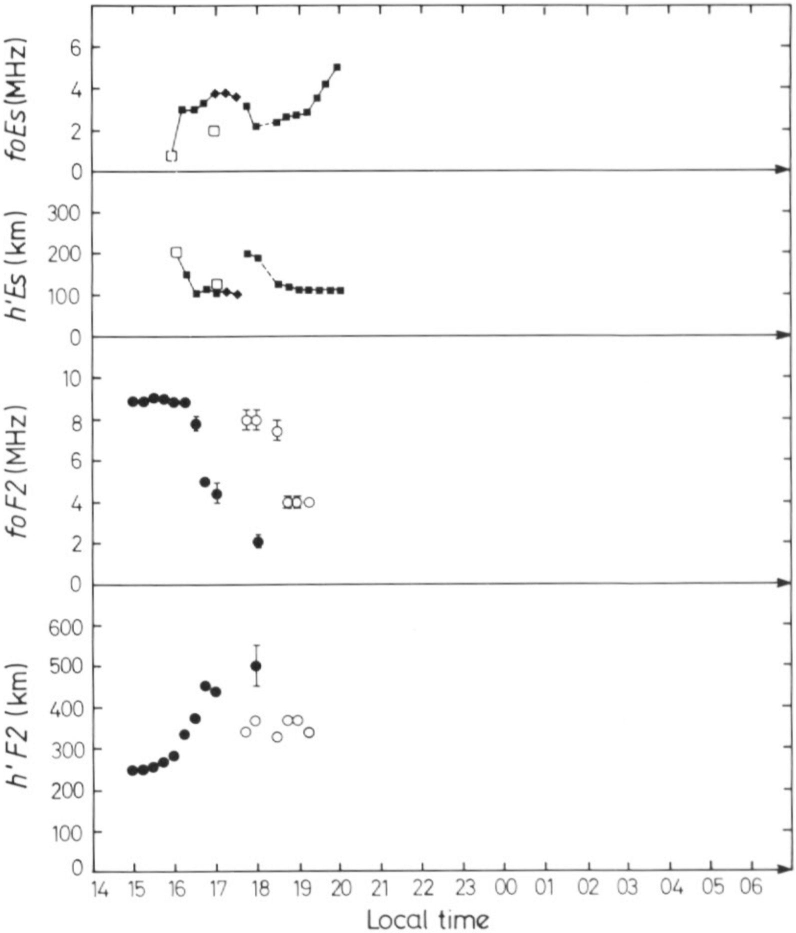


Fig. 3. Variations in critical frequency and virtual height of the *Es* layer (*foEs*, *h'Es*), and in critical frequency and virtual height of the *F2* layer maximum (*foF2* and *h'F2*) for a type 1 trough crossing. 11 May 1980; □ *Es-k*; ■ *Es-r*; ⧫ *Es-f*. *Es* values joined together represent a continuation of the same layer. ● and ○ represent measurements made from the *F*-layers on the equatorward and poleward sides of the mid-latitude trough respectively. Error bars show the uncertainty in individual values.

Table II. A summary of some of the characteristics of *Es* layers (types a, auroral; f, flat; r, retardation; and k, particle, identifying these layers).

| | *Es-f* | *Es-r* | *Es-a* | *Es-k* |
|---|---|---|---|---|
| Approximate semi-thickness (km) | 0.1–1 | 10 | 10 | 10 |
| Location of the main echoing region | Overhead | Oblique | Oblique | Overhead |
| Causes retardation at LF end of *F*-layer trace | No | No | No | Yes |
| Irregularities within *Es* layer (cause diffuse trace) | None | Few | Many | None |
| Associated with particle precipitation | Sometimes | Yes | Yes | Frequently |

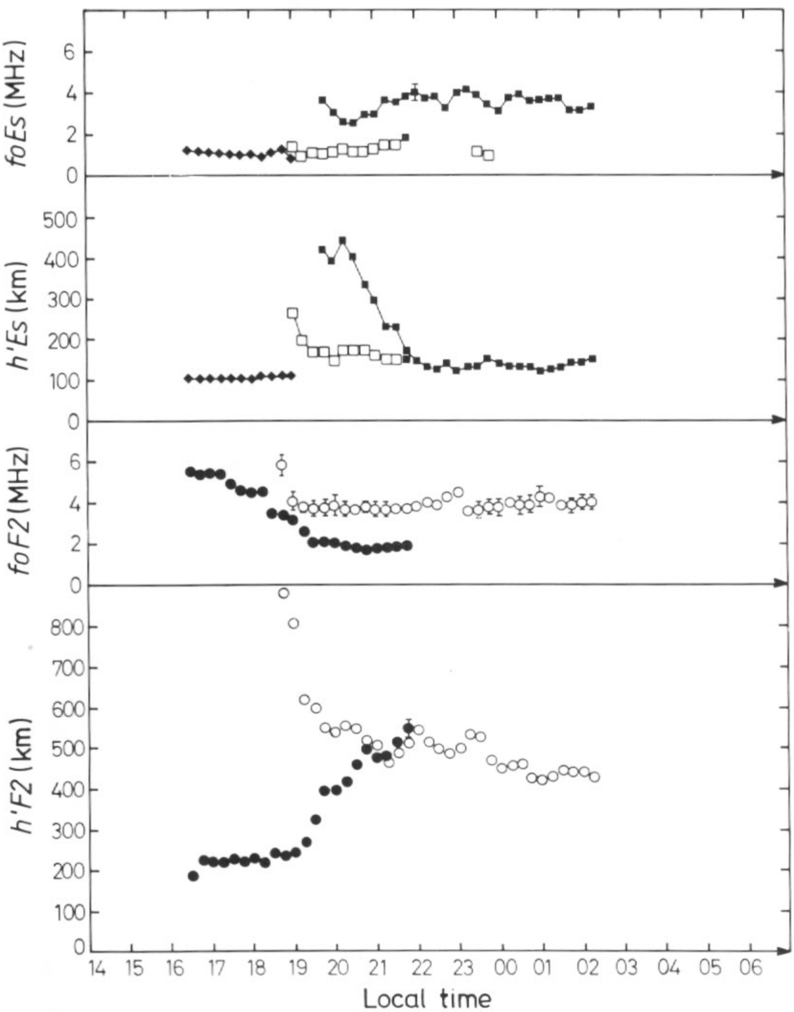


Fig. 4. Variations in *foEs*, *h'Es*, *foF2* and *h'F2* for a type 2 trough crossing. 5–6 May 1980. Symbols as Fig. 3.

of the layer and the latter appears more likely as the received echo strength appears to increase with time.

Many magnetospheric and upper atmospheric phenomena change character about magnetic midnight. Therefore, in this analysis of *Es* under the trough, ten ionogram sequences of type 2 and 3 trough crossings over Halley have been selected to represent pre-midnight conditions and a further ten type 4 crossing events as post-midnight examples. All events are taken from the period from May to July so that there is no significant ionization produced in the *E* region by direct solar radiation between 1800 and 0600 LT. The dates of the samples are given in Table III. Each quarter-hourly ionogram for the two data sets was analysed to determine the position of Halley with respect to the trough. These positions were: equatorward of the trough (position A), under the equatorial edge of the trough (position B), under

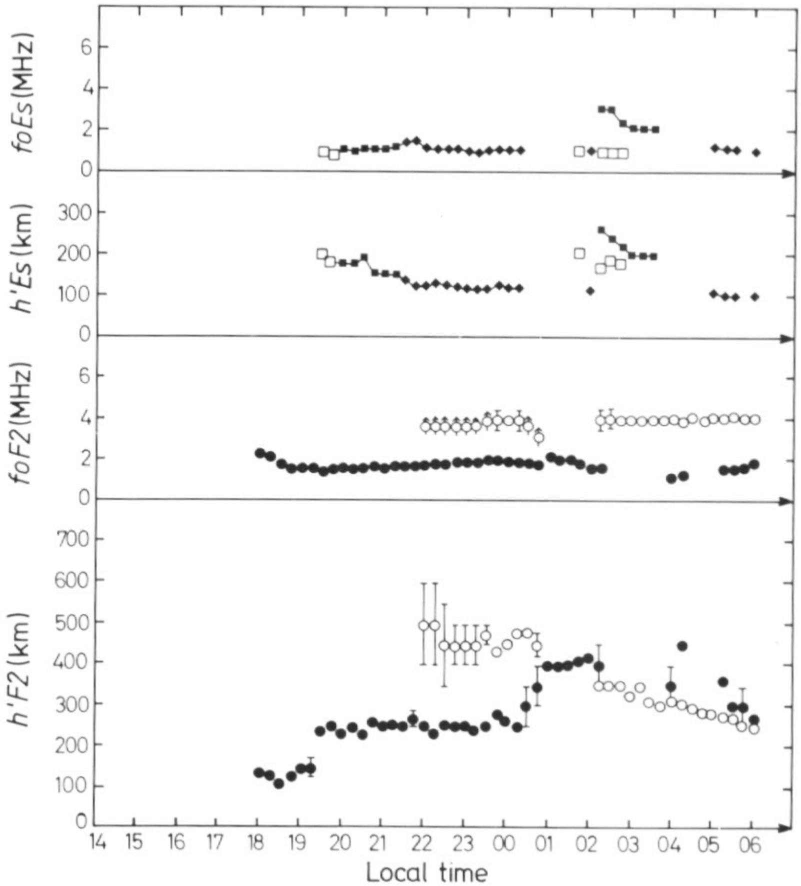


Fig. 5. Variations in *foEs*, *h'Es*, *foF2* and *h'F2* for a type 4 trough crossing, 29–30 May 1980. Symbols as Fig. 3.

Table III. Dates in 1980 of the ionogram sequences from Halley used for detailed analysis of *Es* associated with the mid-latitude ionospheric trough. Magnetic activities are indicated by the maximum local *K* variation recorded during each sequence. For both groups, the analysis was extended for several hours before the event began to several hours after the poleward edge had moved equatorward of Halley.

| *Types 2 and 3 (pre-midnight)* | *Local* $K_{max}$ | *Type 4 (post-midnight)* | *Local* $K_{max}$ |
|---|---|---|---|
| 5 May–6 May | 3 | 3 May–4 May | 2 |
| 6 May–7 May | 3 | 15 May–16 May | 2 |
| 7 May–8 May | 3 | 19 May–20 May | 2 |
| 8 May–9 May | 4 | 29 May–30 May | 2 |
| 9 May–10 May | 3 | 14 June–15 June | 2 |
| 23 May–24 May | 2 | 15 June–16 June | 1 |
| 24 May–25 May | 5 | 18 June–19 June | 2 |
| 25 May–26 May | 3 | 23 June–24 June | 2 |
| 31 May–1 June | 5 | 2 July–3 July | 2 |
| 6 June–7 June | 4 | 13 July–14 July | 3 |

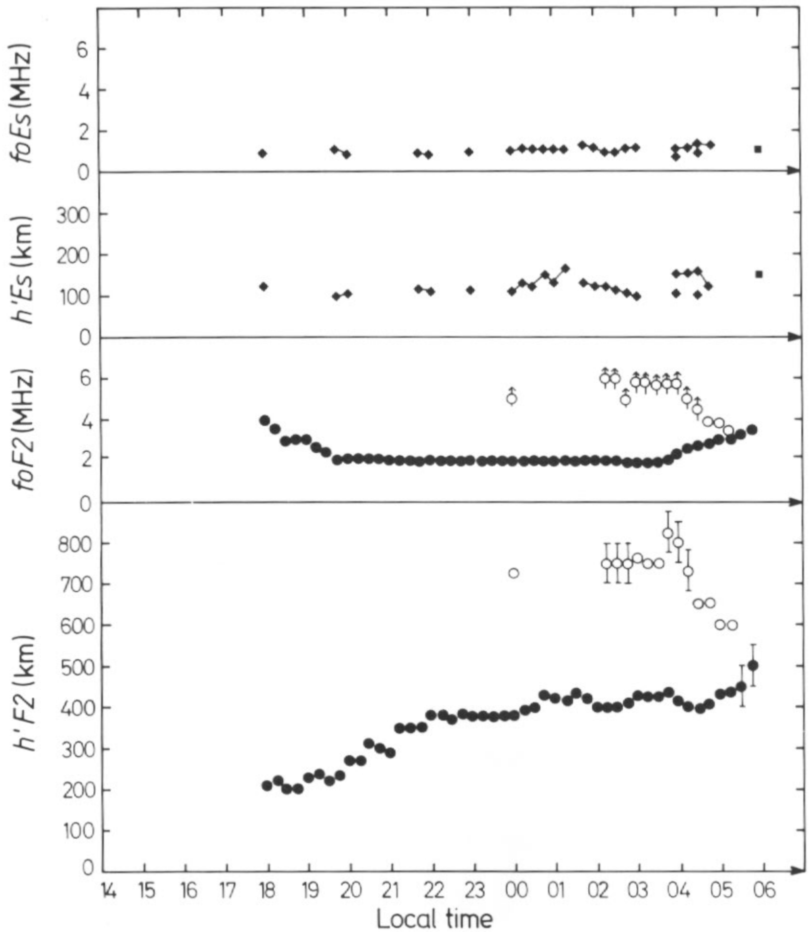


Fig. 6. Variations in *foEs*, *h'Es*, *foF2* and *h'F2* for a type 5 trough event, 10–11 May 1980. Symbols as Fig. 3.

the poleward edge of the trough (position C) and poleward of the trough (position D). It is often difficult to identify uniquely the time when the trough minimum is overhead. Consequently, the *Es* occurrence under this feature has not been determined.

Five ionograms were then selected from roughly the central time of each position, for every sample event, to eliminate as many borderline cases as possible. Five is the limit set by the asymmetry of the trough, the poleward edge normally being much steeper than the equatorward edge (see Fig. 1). Values of the maximum plasma frequency of the *Es* layers, *foEs*, were assigned to frequency bins <1.5, 1.5–1.9, 2.0–2.4, . . . ,4.0–4.4 MHz. Whenever soundings showed two or more *Es* layers present, only that with the higher *foEs* was scaled. The resulting distributions are shown in Figs. 8 and 9, together with the numbers of ionograms showing no *Es* and of those showing no echoes from the ionosphere at all. The latter condition, termed blackout, normally indicates an increase in the absorption of radio waves in the *D* region.

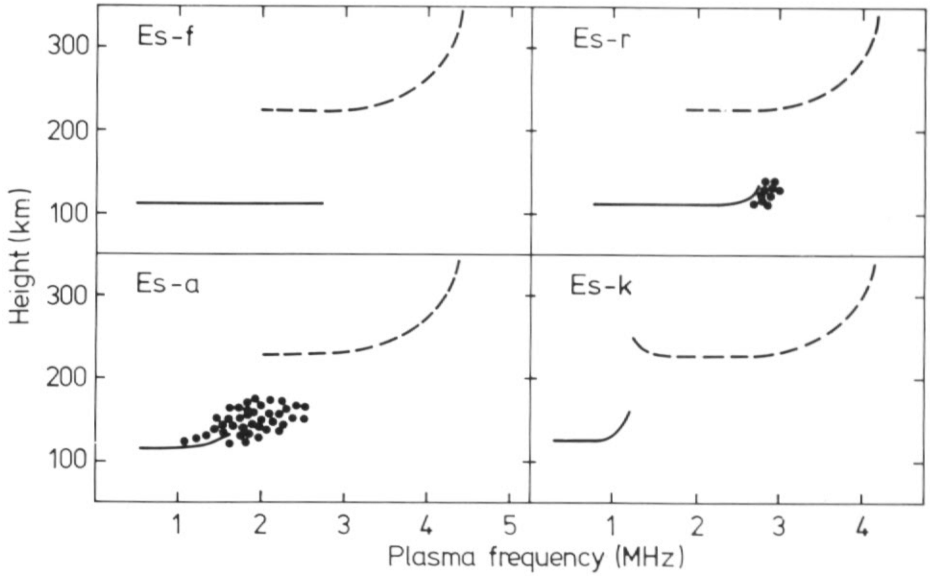


Fig. 7. Line drawing of the four *Es* types observed under the mid-latitude trough at Halley. Solid lines indicate *E*-region echoes, broken lines, *F*-region echoes with stippled areas representing reflections from *E*-region irregularities. Only *o*-mode traces have been shown for clarity and the horizontal scale is in MHz.

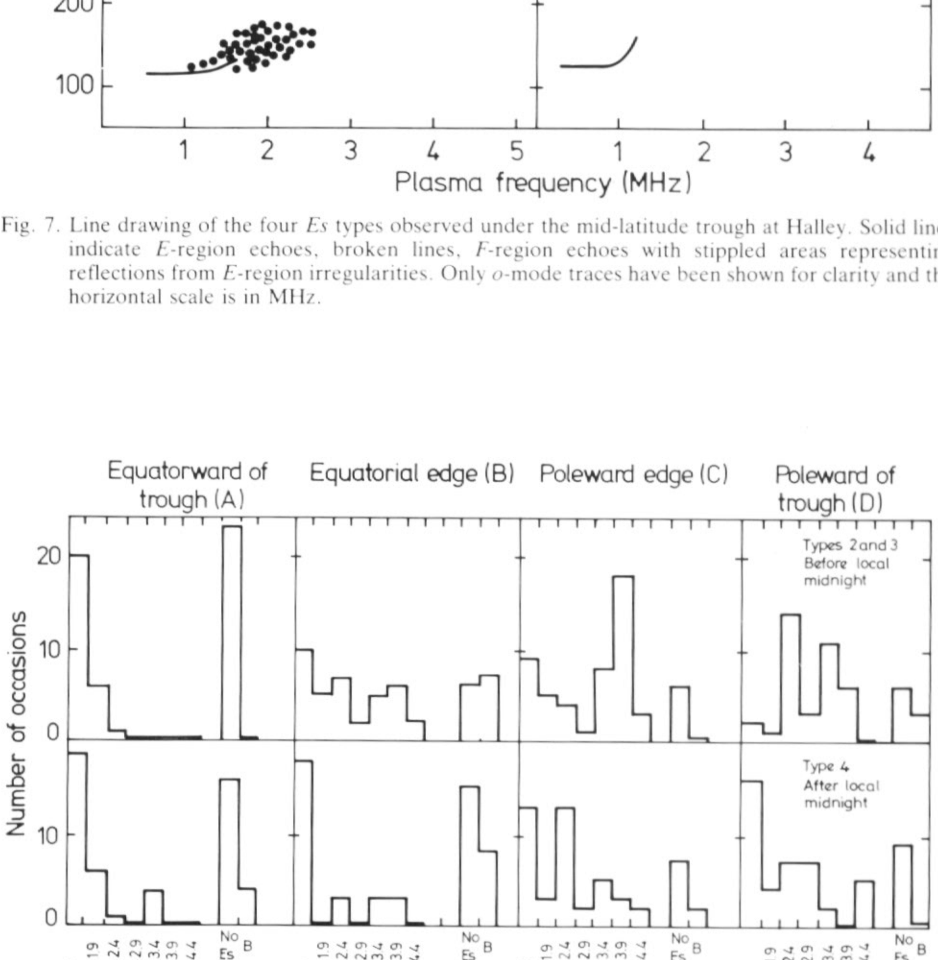


Fig. 8. Distribution of *foEs* values under various features of the mid-latitude trough for events of types 2 and 3 (before midnight) and for events of type 4 (after midnight). Horizontal axes are frequency bins (MHz). Also shown is the occurrence of blackout (B) and the number of occasions when no *Es* was observed.

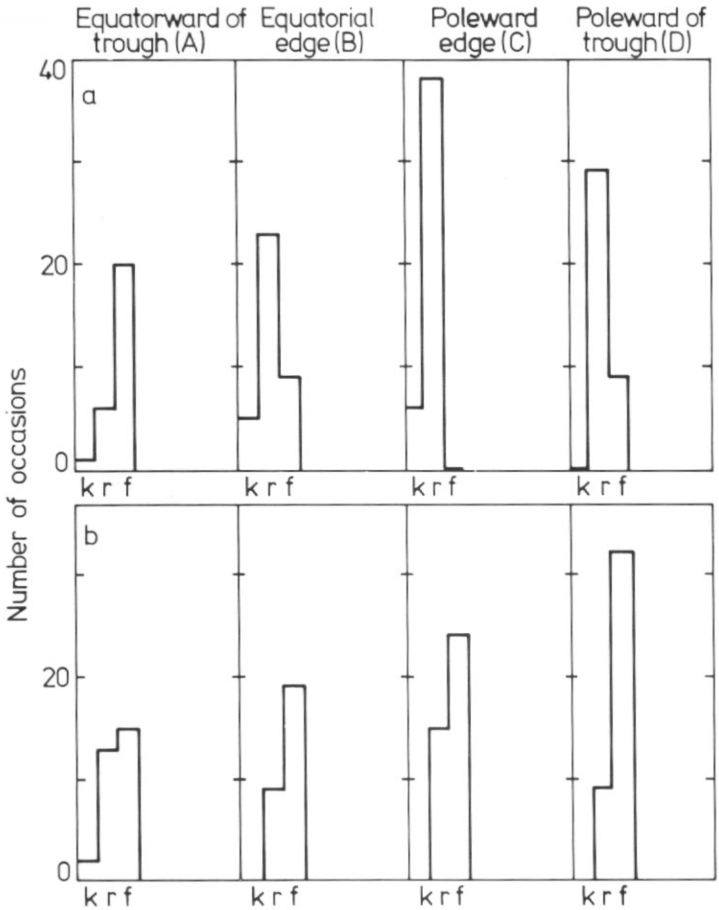


Fig. 9. Distribution of *Es* types under various features of the mid-latitude trough for (a) events of types 2 and 3 (before midnight), and (b) for events of type 4 (after midnight).

Fig. 8 shows that when Halley lies equatorward of the trough, *Es* is observed on about 50% of occasions both before and after magnetic midnight, with *foEs* values normally below 1.5 MHz. These data give an indication of the night-time occurrence of *Es* for a mid-latitude station in winter, which probably results from the normal wind-shear mechanism. *Es* is very frequently seen poleward of position A at all times. Values of *foEs* are normally well above 1.5 MHz and slightly higher before midnight than after. Blackout is seldom seen in positions A and D, being most frequently observed under the trough itself. In this area the *F*-region critical frequency is substantially lower than on either side of the trough, allowing blackout to occur at lower absorption levels there than elsewhere (Rodger and others, 1981).

Analysis of *Es* types (Fig. 9) shows that *Es-f* is usually seen equatorward of the trough at all times. Under the edges of the trough, *Es-r* is the most frequent type before local midnight; after midnight, *Es-f* is more common. Although *Es-k* is not recorded very often, it occurs mostly during the more geomagnetically active crossings before midnight. *Es-f* layers observed prior to the commencement of a

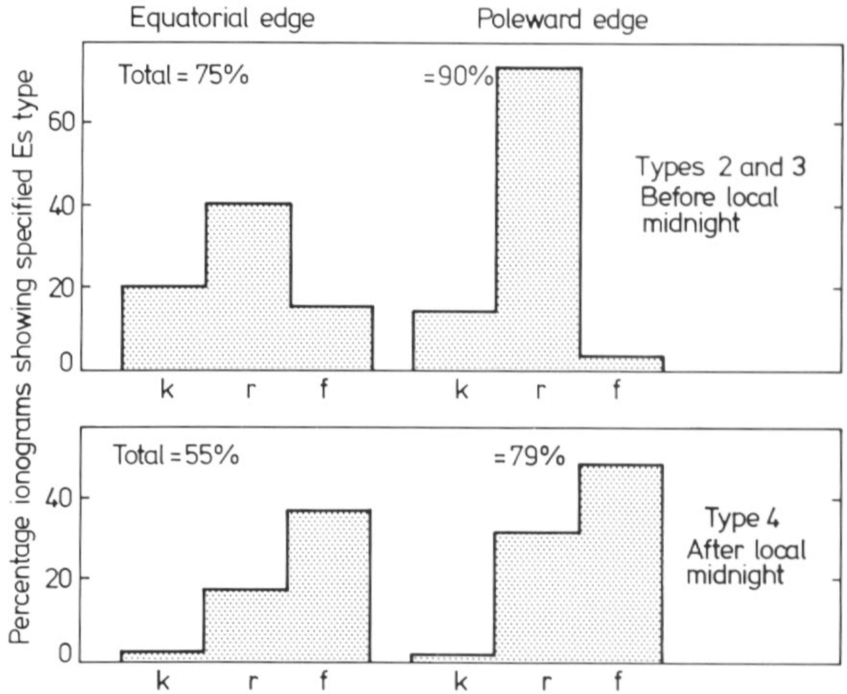


Fig. 10. The percentage occurrence of each *Es* type determined using all possible ionograms recorded under the equatorial and poleward edges of the mid-latitude trough. Before and after local midnight data have been determined using events of types 2 and 3 and events of type 4 respectively.

trough crossing may persist for some time, but generally not through the entire trough crossing. *Es-r* layers, on the other hand, which may first appear as the trough moves overhead, can last for several hours after the poleward edge has passed equatorward of Halley.

To examine more closely the distribution of *Es* below the edges of the trough, the percentage occurrence of each *Es* type has been evaluated using all ionograms under the edges of the trough, treating the data sets from before and after local midnight separately. The results are shown in Fig. 10. The relative probability of occurrence of *Es* types under the equatorward edge of the trough is similar to that under the poleward edge, but is slightly greater for the latter case. The figure also clearly shows the predominance of thick layers (*Es-r* and *Es-k*) before local midnight and of thin layers (*Es-f*) after this time.

The mean values and standard deviations of *foEs* have been evaluated for each *Es* type analysed and are shown in Fig. 11a. The mean minimum virtual height of an *Es* layer measured during its lifetime has been taken to be the best representative value of its overhead height. These have also been averaged and are shown in Fig. 11b. For both figures, data for the equatorward and poleward edges have been amalgamated, but the separation of data before and after midnight has been retained. The *foEs* values for *Es-r* and *Es-f* are similar to each other in both epochs, with pre-midnight values being about 1 MHz higher than those after midnight. The minimum virtual heights of these layers are similar at all times, being near 115 km. Only *Es-k* shows a

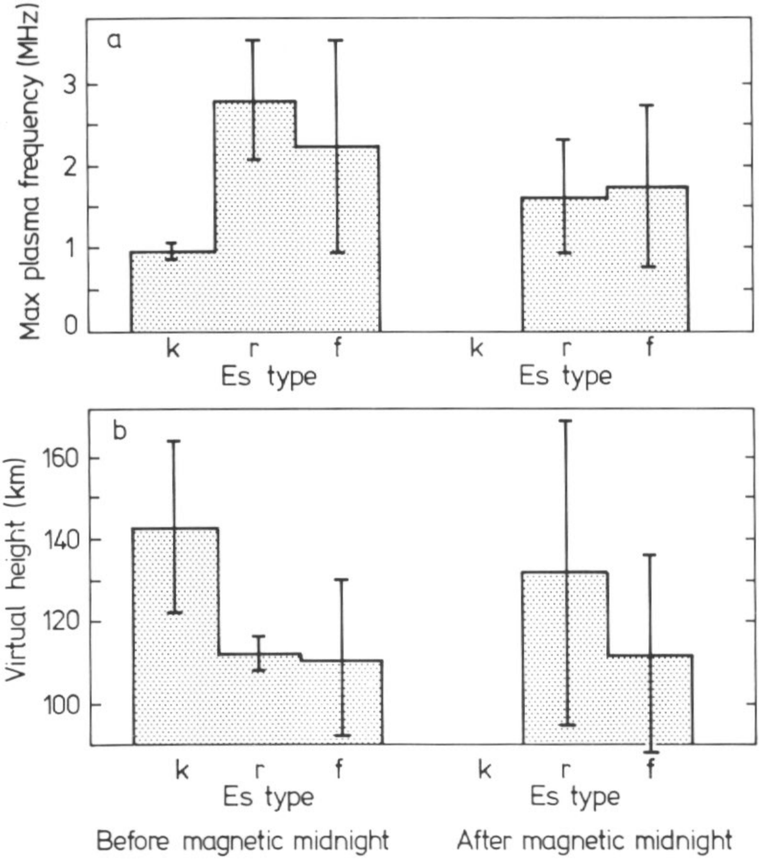


Fig. 11. (a) The mean maximum plasma frequency for each *Es* type observed under the mid-latitude trough. (b) The mean minimum virtual height for each *Es* type observed under the trough. Standard deviations for each value are indicated by the error bars. Data before and after midnight have been determined using events of types 2 and 3 and events of type 4 respectively.

significant difference from the other types, with *foEs* usually only about 1 MHz, and *h'Es* over 140 km.

*Es* behaviour during type 5 trough events (in which the trough remains poleward of Halley throughout the night) cannot be analysed in the manner represented by Figs. 8–11. None the less, a comparison can be made, most easily with type 4 events, of *Es* behaviour between set times. Table IV represents such a comparison made

Table IV. A comparison of *Es* occurrence during events of types 4 and 5 in the 0200–0600 LT sector.

| *Event type* | *Number of soundings showing Es* | *Number of each Es type* | | | *Number of soundings in blackout* |
|---|---|---|---|---|---|
| | | *k* | *r* | *f* | |
| 4 | 81 | 0 | 32 | 49 | 4 |
| 5 | 23 | 0 | 1 | 22 | 4 |

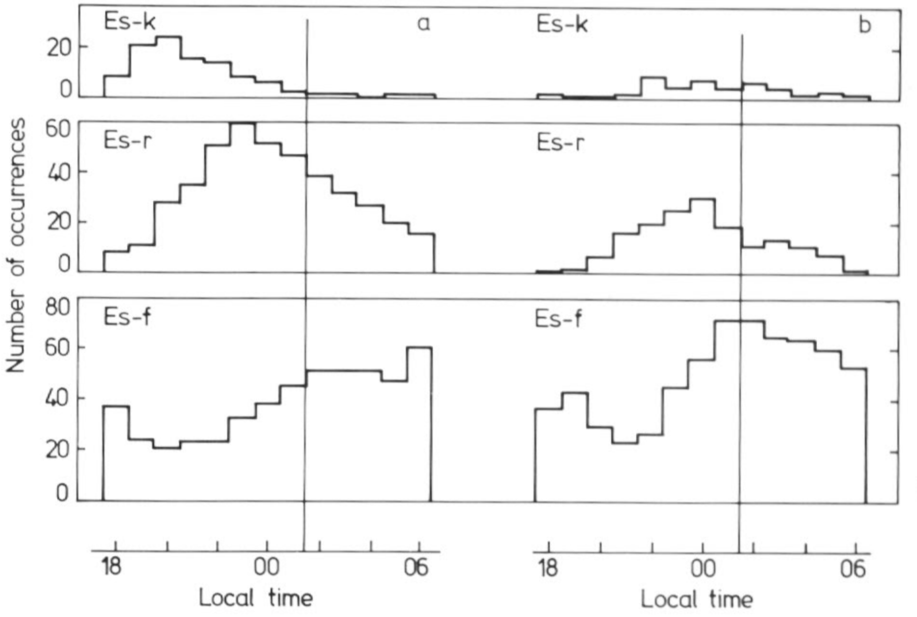


Fig. 12. Variations in the occurrence of *Es* types, *k*, *r* and *f* for (a) Halley in May–July 1978–1980, and (b) SANAE in May–August 1978–1979. The vertical lines through each figure indicate the time of magnetic midnight at the station.

with data from 0200 to 0600 LT inclusive. The samples each consist of ten events, as in the previous analyses, and 17 ionograms from each sequence have been examined. The predominance of *Es-f* in the type 5 data is consistent with that of the post-midnight crossings, as is the occurrence of blackout.

*The overall distribution of night-time Es from May to July*

The mid-latitude trough is observed on Halley ionograms nearly every night during winter. Therefore the winter night-time distributions of *Es* types will be indicative of *Es* occurrence associated with the trough. Fig. 12a shows such distributions obtained from records of routine hourly soundings, taken from May to July of 1978, 1979 and 1980. As usual, no more than one *Es* layer (that with the highest *foEs*) has been counted for each hourly sounding. The data for the three years have been amalgamated in the figure, but show the same, if less pronounced, pattern for the individual winters. Layers with *foEs* less than 1.5 MHz have been ignored, except for *Es-k*, in an effort to remove the background occurrence of mid-latitude *Es* as noted earlier. Auroral *Es* (*Es-a*), is relatively scarce during this period, and has been included in *Es-r* totals. From the nine months' data, a total of 18 days has been lost due to equipment failure. Data from the period May–August in 1978 and 1979 from SANAE station (70° S, 2° W; $L = 4.0$) have been examined in the same way and are shown in Fig. 12b. Both data sets show thick layers (*Es-k* and *Es-r*) predominating before magnetic midnight, with thin layers (*Es-f*) being the most common after this time.

*Summary of observations*

1. *Es* is very common under the trough, especially under its poleward edge.

2. *Es* is more frequent before magnetic midnight than after.
3. *Es-f* is usually seen equatorward of the trough.
4. Relative occurrences of each *Es* type are similar under both edges of the trough.
5. Thick layers (*Es-k*, *Es-r*) predominate before magnetic midnight and persist; thin layers (*Es-f*) are most frequent after magnetic midnight, with *Es-k* rare.
6. Virtual heights of *Es-f* and *Es-r* layers are very similar (around 115 km), both before and after midnight; the virtual heights of *Es-k* layers are much greater (around 140 km).
7. Maximum plasma frequencies of *Es-r* and *Es-f* are approximately the same for comparable times; pre-midnight values are about 1.0 MHz greater than post-midnight values. Maximum plasma frequencies for *Es-k* are only around 1.0 MHz.
8. Blackouts are seen near the trough minimum only.
9. Winter night-time *Es* occurrence at SANAE is similar to that at Halley.

*Estimates of particle fluxes required to form observed layers*

If the minimum virtual heights of observed *Es* layers may be taken as reasonable approximations of their true heights, then these should be accessible to either protons of 10–100 keV energy or electrons of 1–10 keV according to Bailey (1959), considering only *Es* types *r* and *f*. The mean minimum height for these layers being about 115 km, the required particle energies are around 50 keV for protons and 5.6 keV for electrons.

Using the simple method outlined earlier, the particle fluxes required to form the observed layers can now be estimated. Pre-midnight thick layers are normally around 10 km thick, with a mean *foEs* value of 2.8 MHz. The precipitated particles are most likely to be protons, so that the required flux will be around $2 \times 10^6$ cm$^{-2}$ s$^{-1}$.

Post-midnight layers are estimated to be about 1 km thick, and have a mean *foEs* of 1.7 MHz. Electrons are likely to be the dominant precipitating species, so that a flux of around $2 \times 10^5$ cm$^{-2}$ s$^{-1}$ is required to form the post-midnight *Es-f* layers.

## Interpretation and Discussion

Voss and Smith (1980) have shown that energetic proton energy fluxes of the same order of magnitude as the above estimates are observed in the evening sector at the geomagnetic latitude of Halley during disturbed periods ($Kp \simeq 5$). A limitation of the agreement is that they suggest that the plasmapause is about 5° geomagnetic latitude equatorwards of Halley, implying that the trough should also be in this vicinity and that precipitation through gyroresonance may then not be significant. However, the statistical relationships that describe the variations in the positions of the trough and the plasmapause with local time (e.g. Rycroft and Burnell, 1970; Köhnlein and Raitt, 1977) would suggest that Voss and Smith have located the plasmapause too far equatorward for the local time of their data.

Precipitating electron fluxes (e.g. Riedler and Borg, 1972) are in good agreement with those estimated here as necessary for the formation of post-midnight *Es* layers. Whistler mode VLF signals might be expected to be associated with these precipitating electrons, but data from VLF recordings at Halley have not yet been examined for times when *Es* layers are observed after midnight.

Differences in the layer shape before and after midnight cannot be caused solely by the difference in the type of precipitating particles. The assumption made here, of a mono-energetic stream, is acknowledged to be unrealistic, as complex particle energy spectra are normally observed. The high energy particles of the stream will cause ionization at a lower altitude than those forming the peak of the layer. Ionization below the peak of the *Es* layer will cause its ionogram trace to appear more like *Es-r* than *Es-f*. It has not been attempted to evaluate quantitatively the effects that changes in the particle spectra or in the loss cone will have on the observed layers but it is noted that Besprozvannaya and others (1980) concluded that ring current protons are responsible for the production of *Es-r* layers at high latitudes and that other *Es* types are produced by precipitating auroral electrons.

Transport processes, such as redistribution of ionization by neutral winds or electric fields, could provide an alternative mechanism for the differences in the shapes of *Es* layers about midnight. Brekke (1981) states that neutral winds in the high-latitude *E* region may be significant, while Nath and others (1980) suggest that neutral winds only assume importance in this region when precipitating particle fluxes are small. Perhaps the most accurate comment to date on the matter is that of Rino and others (1977) who state that the behaviour of these winds is not well understood. Results from the theoretical model of Fuller-Rowell and Rees (1981) suggest that large winds, with vertical and horizontal shears, can be produced in the high-latitude *E* region by geomagnetic disturbances. Thus, neutral winds may well be important in *Es* behaviour before midnight; for the present the question must remain open.

Both the horizontal and vertical transport of plasma under the action of the dawn–dusk electric field are very important processes in the formation of the trough. The effects of this field in the *E* region will be substantially less, owing to the much greater ion-neutral collision frequency there (Banks, 1980). Other forces, e.g. gravitation and pressure gradients, also influence the distribution and transport of the plasma. Further work is required to assess the relative importance of the various forces acting on the ionospheric plasma under conditions of charged particle precipitation.

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