A WHISTLER STUDY OF THE BULGE REGION OF THE PLASMAPAUSE

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Abstract: Knee whistlers and plasmaspheric whistlers recorded by the VLF goniometer receiver at Halley, Antarctica on 24th June 1977 have been analysed. The knee whistlers were received between 1900 UT and 2300 UT (1630 MLT and 2030 MLT) providing good coverage of the duskside region of the plasmapause. Estimates of the plasmapause position range from L=4.4 at 1700 UT to L=4.7 at 1930 UT and then back to L=4.2 at 2300 UT, as the observing station moved into and through the bulge. Arrival azimuths, nose frequencies and nose travel times were scaled for about 30 ducts inside the plasmasphere and about 10 ducts outside. The azimuths give longitudinal information which, when combined with the determination of the equatorial L-value of a duct using the conventional whistler method, enables its position to be located. Since our analysis technique enables us to process rapidly the large number of whistlers which were observed during this period, we have been able to produce detailed maps of structure near to the plasmapause. Accompanying the anomalously decreasing plasmapause radius after 1730 MLT, where the evening bulge would normally occur, and probably related to it were observed rapid inward drifts of the whistler paths.

1. Introduction

The plasmapause has been much studied experimentally using both satellite observations (CHAPPELL, 1972; RYCROFT, 1975) and by the ground-based whistler method (CARPENTER, 1966; BRICE and SMITH, 1971; RYCROFT, 1974). The latter uses both whistlers with propagation paths inside the plasmasphere and the so-called 'knee-whistlers' (CARPENTER, 1963) propagating outside it. Reports of knee whistlers at stations outside the Siple-Eights-Byrd sector are fairly scarce (though see for example CORCUFF *et al.*, 1972; MATHUR and RYCROFT, 1972; RABE and SCOURFIELD, 1977). Knee whistlers seem to be an infrequent phenomenon at Halley (75.5S, 26.9W) though no statistical survey of their occurrence has yet been

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done.

In this paper we have selected for study a 2.5 hour period near 18 MLT when intense knee whistlers, propagating along several different paths, were observed at Halley. This period 1910–2140 UT 24th June 1977, occurred during the IMS collaborative campaign IPPDYP (International Plasmasphere and Plasmapause Dynamics Programme). We use the single station goniometer technique (BULLOUGH and SAGREDO, 1973) to map the locations of the whistler paths both inside and outside the plasmapause and also the plasmapause itself. We also use the changing nose frequencies of the whistlers to estimate the cross-L drifts of the paths and hence the east-west convection electric field. The results are compared with previous observations.

2. Recording and Analysis of Data

The data used in the study were broad band (0.5–20 kHz) VLF goniometer tape recordings made at Halley (formerly Halley Bay), Antarctica on 24 June 1977, using equipment similar in principle to that described by BULLOUGH and SAGREDO (1973). The observations were either continuous or consisted of one minute recordings at 5 minute intervals (beginning at minute 0, 5, 10 . . . 55). Multicomponent nose whistlers were observed from 1200 UT but no knee whistlers were seen until 1920 UT. After 2400 UT the whistler data deteriorated with the traces becoming indistinct and masked by an intense chorus event.

The tapes were processed using the Sheffield University semi-automated whistler analyser (SMITH *et al.*, 1979). A spectrogram of a typical event during the knee whistler period is shown in Fig. 1. The various components were scaled for nose frequency f_n and azimuth of arrival. Only nose whistlers were used so that the nose frequency could be measured directly in every case. The results for components in successive events corresponding to the same path were averaged to reduce the effect of random errors. The L-value of each whistler duct was found

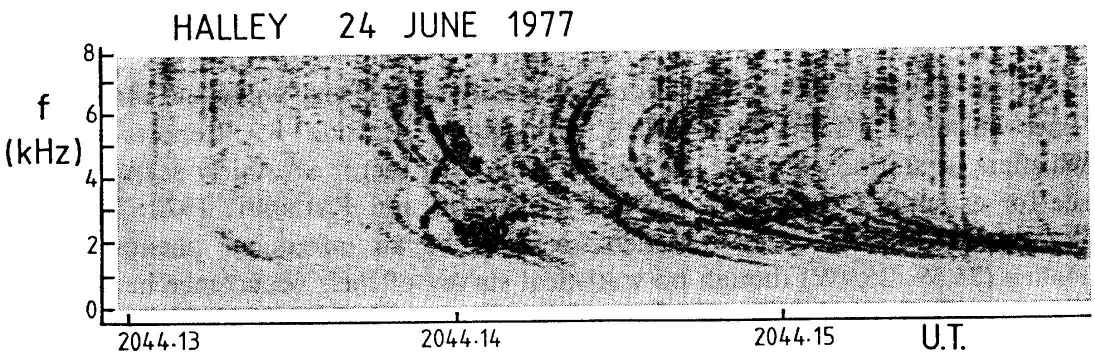

Fig. 1. A spectrogram of a typical multicomponent whistler received at Halley during the period 2020–2140 UT, 24 June 1977, showing the large number of "knee" traces.

from the corresponding nose frequency by the standard method (PARK, 1972). A dipole magnetic field model was used and diffusive equilibrium and collisionless plasma electron density distribution models employed for whistler paths inside and outside the plasmapause respectively.

The observations were made during a time of moderately quiet magnetic conditions (see Fig. 2) with $Kp=1$ to 2 though there had been some minor disturbance ($Kp=4$) 2 days earlier.

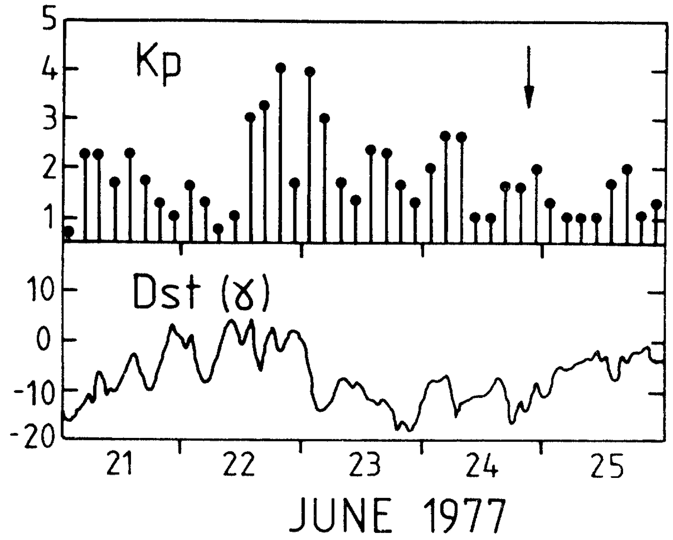

Fig. 2. Magnetic activity indicated by indices Kp and Dst during and before the period studied. The arrow indicates the time of the observations.

3. Plasmapause Equatorial Radius

The plasmapause equatorial radius, as deduced from whistlers seen at Halley, is plotted in Fig. 3 as a function of UT and MLT ($\simeq$UT$-$3 hr). The open circles indicate 60 minute averages of the L-value of the outermost plasmaspheric whistler path seen (not necessarily the same path from event to event); the circled dots are similar 30 minute averages; and the circled crosses are 30 minute averages of the L-value of the innermost knee whistler path. The longitude and hence MLT of the whistler path can differ from that of the observing station by an amount corresponding to half the longitudinal width of the viewing window of the latter. CARPENTER (1966) estimates this to be about 15° (1 hr) for Eights and Byrd though the goniometer determinations of Section 4 would suggest about half this value for Halley in the present case. Although the curve shown before 16 MLT strictly speaking only defines the innermost possible limit of the plasmapause we will, following CARPENTER (1966), make the usual assumption that it indicates the plasmapause equatorial radius L_{pp} fairly closely. After 16 MLT when knee whistlers first occur, the

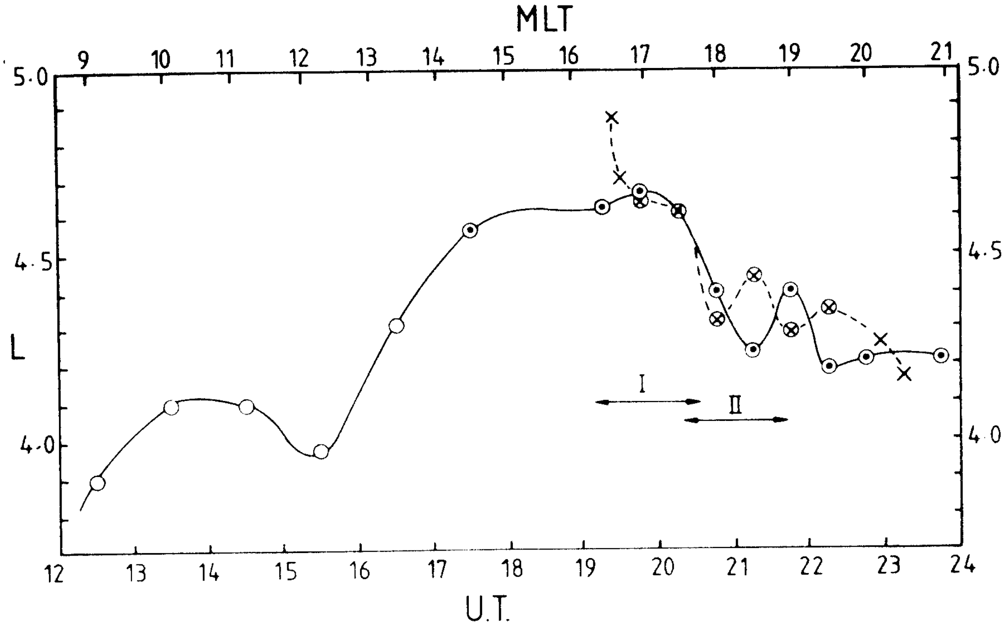

Fig. 3. Estimated plasmapause equatorial radius estimated from whistlers observed at Halley on 24 June 1977.
Open circle: 60-minute mean of highest latitude plasmaspheric whistler.
Circled dot: 30-minute mean of highest latitude plasmaspheric whistler.
Circled cross: 30-minute mean of lowest latitude knee whistler.
Cross: individual knee whistlers.
I and II indicate the periods examined in more detail in Figs. 4 and 5.

plasmapause is unambiguously defined and L_{pp} decreases rapidly from 4.7 at 17 MLT to 4.3 at 18 MLT and then more slowly to 4.2 at 20 MLT.

There would appear to be a bulge centred on 16 MLT—rather earlier than the average bulge for moderate steady magnetic conditions found by CARPENTER (1966). L_{pp} increases from about 4 at 12 MLT to 4.5 at 14 MLT and this could correspond to the station moving into an early bulge encounter as described by CARPENTER (1970) and which he ascribed to a sunward surge of duskside bulge plasma released by an isolated substorm. The observed bulge is not dissimilar (though 0.5–0.7 L closer in) to the earlier of the two bulges observed by RABE and SCOURFIELD (1977) from Sanae whistlers; they identify their double bulge with CARPENTER's (1966) plasmapause contour rotated 3 hr eastwards following the onset of quiet conditions.

From 18 MLT to 20 MLT there is clear evidence of longitudinal structure in the plasmapause surface, since the knee whistler curve in Fig. 3 at times crosses below the plasmaspheric whistler curve. This can only be explained if L_{pp} varies across the range of longitude in the viewing window of the observing station at the time (see PARK and SEELY, 1976).

4. Whistler Duct Locations

Two periods near dusk, 1910–2030 UT and 2020–2140 UT, were selected for detailed study. Fig. 4 shows the mean positions of the exit points into the earth-ionosphere waveguide for whistler components corresponding to various ducts observed during the first period. The points represent a mean over typically 15–25 events, and are plotted on a great circle map using the mean arrival azimuth determined by the goniometer and the mean L-value at 100 km altitude. The latter

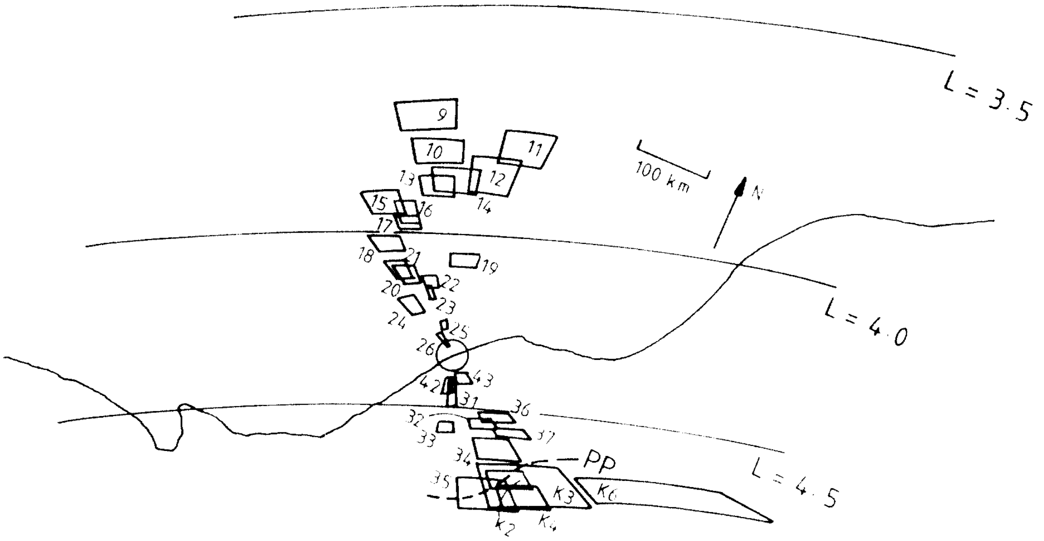

Fig. 4. Great circle map centred on Halley, showing the mean locations of the exit points of ducted whistler components into the earth-ionosphere waveguide, deduced from VLF goniometer recordings made 1910 UT–2030 UT, 24 June 1977. The size of the boxes represents the positional uncertainty calculated from the standard errors of the mean nose frequency and arrival azimuth determinations. The identification numbers prefixed with a K are knee components. The deduced plasmapause position is marked PP.

was calculated by using the invariant latitude tables of EVANS *et al.* (1969), and following SAGREDO and BULLOUGH (1973) in assuming that the L-value at the exit point is the same as that at the equator, as calculated from the whistler nose frequency. This assumes that propagation continues to be field-aligned between where the whistler leaves its field-aligned duct, which may be at altitudes as great as 1500–2000 km (BERNHARDT and PARK, 1977; STRANGEWAYS, 1978; THOMSON and DOWDEN, 1978), and where it enters the waveguide. Multi-station triangulation studies (RYCROFT *et al.*, 1974; MATTHEWS *et al.*, 1979) and ray tracing work (THOMSON and DOWDEN, 1978) have shown that this assumption may lead to the exit point L-value being over-estimated by 0.2–0.6. The use of the dipole field model rather than a more realistic model for the geomagnetic field (PARK and

SEELY, 1976) may also contribute to this error. The boxes of Fig. 4 show the uncertainty in the mean duct locations due to random errors and are not intended to indicate in any way the cross-section of the ducts.

In Fig. 5 we have replotted the data in the equatorial plane, by mapping along field lines. The whistler path L-values are now correct, since they are determined by the corresponding whistler nose frequency which is a function of the equatorial gyrofrequency. Errors in longitude will be due partly to bearing errors and partly to any non-field-aligned propagation at low altitudes as discussed above. The former, which are appreciable only for exit points near to the observing station, are typically due to the combined effect of polarization and multipath errors, and as shown by STRANGEWAYS (1978) these often tend to cancel out for the crossed-loop goniometer technique. The latter will have relatively little effect for exit points which are predeterminantly situated north and south of the station, as in the present case. We therefore believe that Fig. 5 is a good representation of the pattern of whistler ducts as they cross the equatorial plane.

Fig. 5 shows a complex structure of ducts inside the plasmasphere. In fact not all of the 30–35 ducts observed during the period are plotted; some low latitude paths

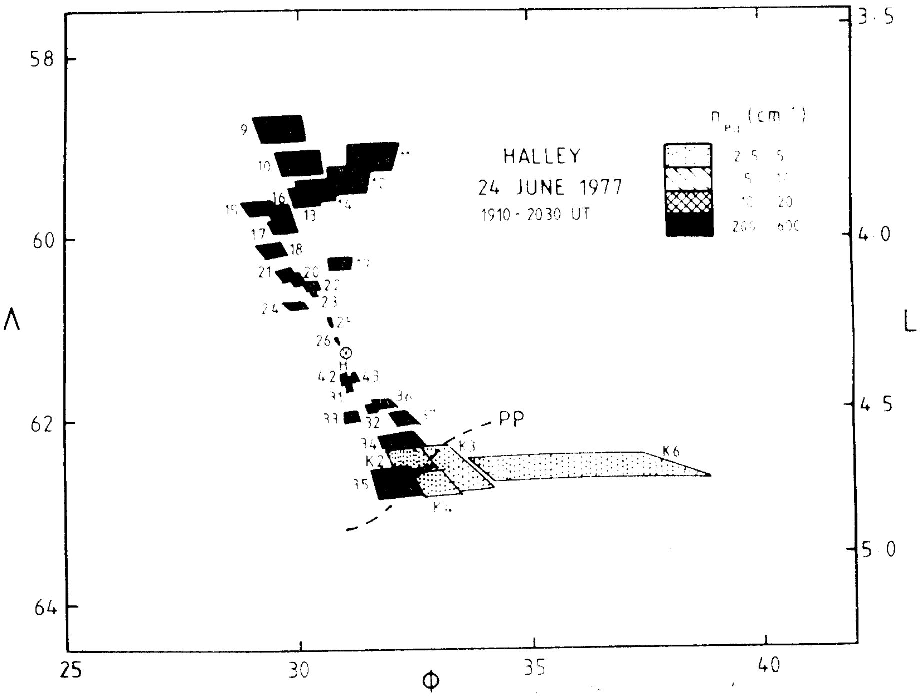

Fig. 5. This shows the whistler ducts of Fig. 4 mapped up to the equatorial plane and plotted in L—Φ (invariant longitude) space. Λ (=arc cos ($L^{-1/2}$)) is the invariant latitude of the whistler exit points assuming field-aligned propagation. Circled cross H denotes the Halley field line. Equatorial electron densities, obtained from the whistler data, are shown by shading.

produced non-nose whistler components and were not scaled; other components appeared to exit almost directly overhead and were omitted from the plot for clarity. The duct pattern seems to have a linear structure reminiscent of SAGREDO and BULLOUGH (1973) though with a different direction, in this case being elongated approximately along the geomagnetic invariant meridian through Halley.

There are relatively few knee paths (no more than 5) during this first period and they are significantly poleward of Halley. The plasmapause position, which has been drawn between the plasmaspheric and knee paths, lies at about $L_{pp}=4.6$. There is some hint of a decreasing L_{pp} with longitude from west to east which would correspond to the decrease with local time shown in Fig. 3 from 1900–2030 UT.

Fig. 6 is a similar diagram to Fig. 5 but for the second period. The ducts shown are not necessarily identified with any of those of the first period; the pattern of the whistler spectra changes from one period to the other making such identification difficult. There are some striking differences between the two periods. There are now fewer paths (about 20) inside the plasmasphere but far more knee paths outside (about 15) with L-values up to $\sim$5.2. As a whole the duct pattern occupies a region of larger extent in both L (increase from 1 R_E to 1.5 R_E) and longitude (increase from 7° to 15°) than during the first period. The structure is less linear in appearance.

The plasmapause is again shown and it is clear that it has moved considerably

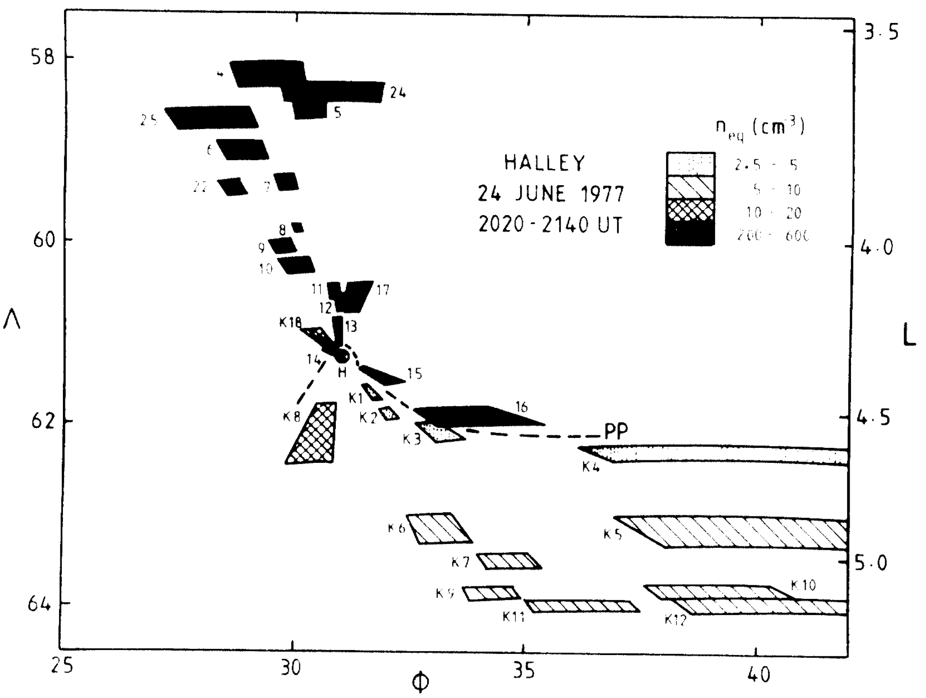

Fig. 6. Similar to Fig. 5 for the second period 2020–2140 UT 24 June 1977.

equatorward to pass almost directly overhead at Halley as is also indicated in Fig. 3 between 20–21 UT. There appears to be evidence of an inward "kink" or ripple of about 0.4 L on the plasmapause surface, which can probably be identified with the earlier of the two dips in the knee curve of Fig. 3. It has been suggested by KAISER (1972) that such structures are produced by fluctuations in the dawn-dusk electric field (associated with substorm activity) and that these then co-rotate with the earth (KAVANAGH *et al.*, 1968) into the local time sector where they are observed. Similar co-rotating structures have been seen by LEFEUVRE and BULLOUGH (1973) on the Ariel 3 satellite. Some of the knee paths (*e.g.* K1, K2, K3) could be associated with the trapping of whistlers in surface irregularities of the plasmapause surface. Irregularities in the plasmapause surface have also been observed by PARK and CARPENTER (1970), MORGAN and MAYNARD (1976), LEWIS *et al.* (1977), CARPENTER (1978a).

5. Equatorial Electron Densities

The mean equatorial electron density for each whistler duct in each of the two periods studied was calculated from the nose travel times. The results are shown coarsely by shading in Figs. 5 and 6 and in more detail in Fig. 7. The plasmapause,

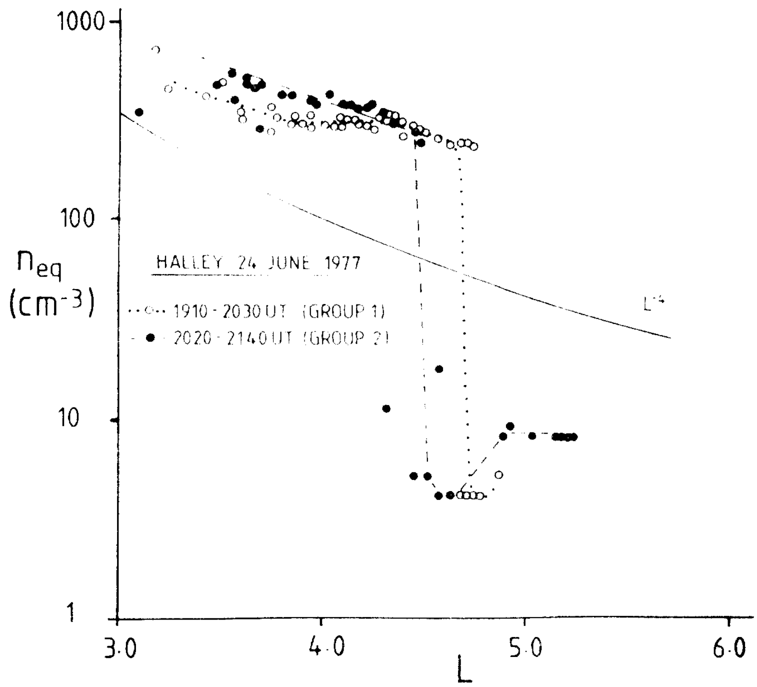

Fig. 7. Equatorial electron density profiles for the two periods studied. Each point represents the density for one whistler duct, averaged over the appropriate period. The L^{-4} curve shown for comparison is normalized to 100 cm^{-3} at $L=4$.

at which the density drops sharply by two orders of magnitude, can be clearly seen to move inwards by $0.2L$ in an hour. Inside the plasmapause, the density roughly follows an L^{-4} profile though there is evidence to suggest that it has increased slightly from the second period to the first. Just outside the plasmapause there is a deep trough, but a little further out, the plasma density increases again by about a factor of two; this is shown clearly in Fig. 6 where the ducts K1–K4 lie in the trough immediately outside the plasmapause, while the other knee ducts form a region of somewhat higher density, reminiscent of a detached plasma region as described by CHAPPELL (1974).

6. Drifts

Fig. 8 summarises the cross-L drifts of some of the observed whistler paths deduced from the nose frequencies f_n of the corresponding whistler components observed during the two periods of Section 4. For clarity not all ducts shown in Figs. 5 and 6 are represented in Fig. 8. Fifteen minute averages were used. It is assumed that the changing f_n's are due to a westward magnetospheric convection electric field E_w (CARPENTER *et al.*, 1972) and since the magnetic activity is low (Fig. 2) it is assumed that the $\partial B/\partial t$ contribution discussed by BLOCK and CARPENTER (1974) and the ring current effects of SAGREDO and BULLOUGH (1972) may be neglected. On this assumption, $E_w=2.1\times10^{-2}\ d/dt\ (f_n^{2/3})$ V/m (PARK, 1978). The vertical scale in Fig. 8 is linear in $f_n^{2/3}$ so that the east-west field inferred from a drifting duct is proportional to the gradient of the corresponding line, as indicated in the bottom left corner of the diagram.

The drifts are predominantly cross-L. No longitudinal drifts relative to the observing station, which would indicate a radial (at the equator) component of the convection field, could be detected from the azimuth data. However, it should be stated that the goniometer method for determining longitudinal motions is not very sensitive on account of random bearing errors (SMITH *et al.*, 1979); the resolution achievable depends on the latitude of the duct being tracked and the geometry of its line of sight from the observing station relative to the magnetic meridian, but is not likely to be better than about 0.1 mV/m (equatorial radial field component).

The observed cross-L drifts are small during the first period, possibly a westward field $E_w\lesssim0.1$ mV/m is present. However, there is a significant inward drift over a wide range of L-shells during the second period. Near $L=3.8$, $E_w\simeq0.3$ mV/m but at greater distances from the earth the field is nearer 0.1 mV/m. This is in agreement with the decreasing drift with increasing L found by CARPENTER (1978b) during magnetically quiet times, and attributed by him to a midlatitude dynamo process. Regression analysis shows a mean $E_W=(0.14\pm0.03)$ mV/m inside the plasmapause and (0.13 ± 0.02) mV/m outside, showing that there is no significant change across the plasmapause boundary, *i.e.* there is no shielding

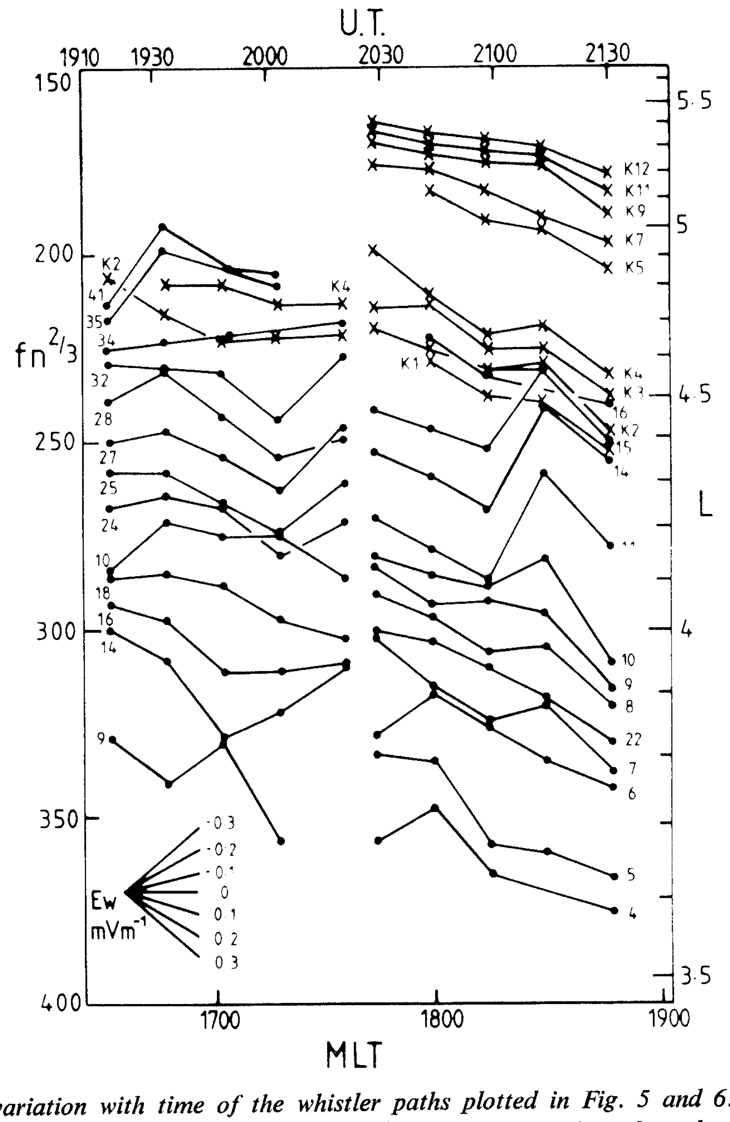

Fig. 8. L-variation with time of the whistler paths plotted in Fig. 5 and 6. The vertical scale is linear in $f_n^{2/3}$ since $d/dt\ (f_n^{2/3})$ is proportional to the value of the inferred westward convection electric field E_W, as indicated in the bottom left hand corner. Note the large scale ($3.5<L<5.5$) inward drift in the second period. Cross = knee whistler; dot = plasmaspheric whistler.

effect. The decreasing plasmapause radius therefore appears to be a consequence of the fact that both the dense plasma inside the boundary and the tenuous plasma outside it, as detected by the motion of the embedded field-aligned whistler ducts, are drifting inwards at the same rate.

There appears to be a significant outward surge of some of the ducts near $L=4.4$ at 2115 UT. The effect is transmitted with increasing attenuation to both lower L shells and higher ones across the plasmapause boundary. It is not clear whether this is a temporal or spatial fluctuation but if the former, it could be caused by a rapid substorm induced fluctuation in the convection field.

7. Discussion

The observed plasmapause location for the period studied, as shown in Fig. 3, is replotted in Fig. 9 as a polar diagram in the equatorial plane. Also shown are the average plasmapauses of CARPENTER (1966) (dashed line marked C) and CHAPPELL *et al.* (1971) (dotted line marked CHS) and the double bulge contour of RABE and SCOURFIELD (1977) (dashed line marked RS). The dayside plasmapause (before 17 MLT) lies in this case between the average plasmapauses of CARPENTER (1966) and CHAPPELL *et al.* (1971), rather closer to the latter, which is not unexpected for the moderately quiet magnetic conditions prevailing at the time. However in the dusk and post-dusk sector the plasmapause radius decreases by about 0.5 L until

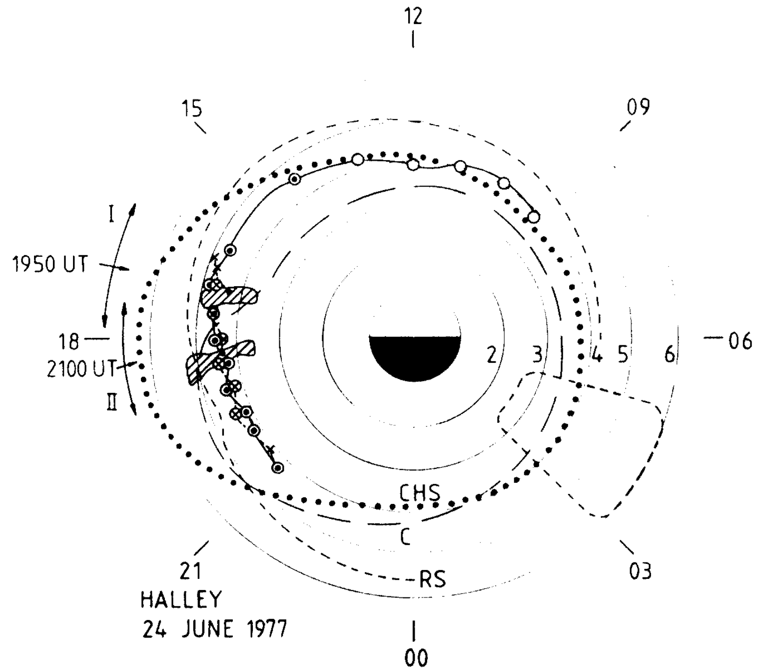

Fig. 9. The estimated plasmapause position of Fig. 3 is replotted on a L-MLT diagram in the equatorial plane. The symbols have the same meanings. Also shown for comparison are the average plasmapause contours of
CARPENTER (1966) — — C
CHAPPELL et al. (1971) · · · · · CHS
and the double bulge of
RABE and SCOURFIELD (1977) - - - - - RS.
The two shaded regions show the extent of the observed ducts patterns at the middle of the periods I and II represented by Figs. 4 and 5. The Eights Station viewing window assumed by CARPENTER (1966) is shown (at 4 MLT) for comparison.

it lies well inside both average contours. This is rather surprising. If the plasmapause had been contracted by loss of plasma during previous disturbed conditions, for example the $Kp=4$ period on 22 June, and not yet recovered by the filling of flux tubes from the ionosphere, then one would not expect it to extend out so far in the afternoon sector. In all theories of plasmasphere creation involving magnetospheric convection (*e.g.* KAVANAGH *et al.*, 1968; RYCROFT, 1974), some sort of bulge would be expected on the dusk side, which is not observed in the present case.

The quite rapid inward drifts seen after dusk are also not in agreement with the generally outward drift (eastward electric field) normally observed in this local time sector in both quiet (CARPENTER and SEELY, 1976) and disturbed (PARK, 1976) times. There have, however, been examples of inward drifts reported for example by SAGREDO *et al.* (1973) who deduced a westward field of 0.2 mV/m during a quiet period from a drifting whistler path observed from Halley at around 18 MLT. MORGAN (1976) also presents diagrams which show the inward drifting of whistler ducts seen from Alaskan stations in the post-dusk sector.

We tentatively suggest that the rapid inward drifts and the decreasing plasmapause radius are connected and are possibly caused by a sudden substorm related increase in the westward convection field which is sufficient to overcome the normal tendency of the plasma to stagnate on the dusk side. The unusually complex structure of field-aligned whistler paths excited outside the plasmasphere may be due to regions of detached plasma (CHAPPELL, 1974; CHAPPELL *et al.*, 1971; PARK and SEELY, 1976; WARNER and ORR, 1979) which have been convected inwards by the same convection field.

Some of the problems raised by this study could probably be resolved by reference to the whistler data received simultaneously at the neighbouring $L=4$ stations of Sanae and Siple which collaborated in the IPPDYP programme. Initial examination of the records reveals that similar whistlers to those at Halley were observed at Siple, whereas no whistlers were recorded at Sanae. It is hoped to undertake a closer study in the future.

Fig. 9 also shows the extent of the ducts shown in Figs. 5 and 6 mapped into the equatorial plane; on this occasion the viewing window is rather smaller than that assumed by CARPENTER (1966) for Eights Station. Also of interest during this period is a power line harmonic radiation event observed between 2010–2018 UT with associated triggered emissions (J. P. MATTHEWS, personal communication) similar to those reported by HELLIWELL *et al.* (1975) from Siple/Roberval data. Such events are rare at Halley and the fact that the emissions had no observable goniometer modulation and that no such event appears to have been simultaneously recorded at either Siple or Sanae suggests that it occurred close to the Halley field line, and hence to the plasmapause surface which was nearby at that time. CARPENTER (1978a) reported special effects associated with propagation near the plasmapause surface and it may be that the steep electron density gradient across it is favourable for the generation of localized phenomena such as the PLHR event mentioned above. It was probably generated in one of the many whistler ducts seen near the plasmapause at this time.

8. Conclusions

An investigation of the plasmapause has been carried out using Halley VLF goniometer recordings made on one moderately quiet day during the IMS when knee whistlers were recorded. An early bulge is found around 16 MLT similar to that of RABE and SCOURFIELD (1977). After 18 MLT there was found to be no evening bulge but the plasmapause moved rapidly inwards. At the same time there was an inward drift of all whistler paths both inside and outside the plasmasphere. Direction-finding enabled the positions of the many ducts present to be plotted, and revealed detailed duct structure corresponding to both plasmaspheric and knee whistlers. Whistler derived plasma density measurements showed a deep trough just outside the plasmapause, and a detailed plasma region further out.

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