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OUTLYING PLASMASPHERE STRUCTURE DETECTED BY WHISTLERS

D. HO and D. L. CARPENTER
Radioscience Laboratory, Stanford University, Stanford, CA 94305, U.S.A.

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Abstract—Whistlers recorded at Eights ($L \simeq 4$) and Byrd ($L \simeq 7$), Antarctica have been used to study large-scale structure in equatorial plasma density at geocentric distances $\simeq$3–6 R_E. The observations were made during conditions of magnetic quieting following moderate disturbance. The structures were detected by a "scanning" process involving relative motion, at about one tenth of the Earth's angular velocity or greater, between the observed density features and the observing whistler station or stations. Three case studies are described, from 26 March 1965, 11 May 1965 and 29 August 1966. The cases support satellite results by showing outlying high density regions at $\simeq$4–6 R_E that are separated from the main plasmasphere by trough-like depressions ranging in width from $\simeq$0.2 to 1 R_E. The structures evidently endured for periods of 12 hr or more. In the cases of deepest quieting their slow east–west motions with respect to the Earth are probably of dynamo origin. The cases observed during deep quieting (11 May 1965 and 29 August 1966) suggest the approximate rotation with the Earth of structure formed during previous moderate disturbance activity in the dusk sector. The third case, from 26 March 1965, may represent a structure formed near local midnight. The reported structures appear to be closely related to the bulge phenomenon. The present work supports other experimental and theoretical evidence that the dusk sector is one of major importance in the generation of outlying density structure. It is inferred that irregularities of the type reported here regularly develop near 4–5 R_E during moderate substorm activity. This research suggests that at least a major class of the density structures that develop near 4 R_E are tail-like in nature, joined to the main body of the plasmasphere. The apparent disagreement with Chappell's results from OGO 5, which are interpreted as showing regions of "detached" plasma beyond 5 R_E, may be related to the pronounced spatial structure of electric fields observed in high-latitude ionospheric regions that are conjugate to the magnetospheric regions in which the OGO-5 observations were made.

INTRODUCTION

The plasma structure of the middle magnetosphere is of interest because it is apparently very sensitive to convection activity and provides a way of inferring certain properties of that convection. For example, the observation of a bulge or region of larger plasmasphere radius in the dusk sector (Carpenter, 1966) served as a basis for a number of studies of magnetospheric electric fields and general convection physics (e.g. Brice, 1967; Nishida, 1966, 1971; Wolf, 1970; Grebowsky, 1970).

Satellite probes have revealed the existence of regions of dense plasma beyond the typical plasmasphere radius (Chappell *et al.*, 1970; Taylor *et al.*, 1970; Chappell, 1974). These regions tend to occur in the afternoon sector, where the results of interaction between convection and corotation effects might be expected to be particularly well defined (Axford and Hines, 1961; Brice, 1967).

The density variations at the boundaries of the plasmasphere and outlying regions imply abrupt spatial variations in the conditions for Landau and cyclotron–resonance interactions between waves and particles; at or near the boundaries there may be strong effects involving ulf–vlf waves and the non-thermal magnetospheric particle populations (e.g. Thorne, 1975). Outlying structure of the plasmasphere may provide localized and thus conveniently observable examples of such effects, in the manner discussed by Kivelson and Russell (1973).

Our knowledge of outlying density structure, although limited, is steadily increasing. Whistler studies have shown the duskside plasmasphere bulge to be dynamic in nature, being displaced westward into the afternoon sector during substorm periods and drifting eastward into the premidnight sector during quieting (Carpenter, 1970). Chappell (1974) has summarized a relatively large body of data on thermal ion density from OGO 5. He concludes that outlying structures extending along the satellite orbit for distances of order 1 R_E and exhibiting much fine structure are "detached" from the main body of the plasmasphere. Chen and Grebowsky (1974) sought to model the OGO 5 observations by combining a dawn–dusk magnetospheric electric field with a field associated with the Earth's rotation and varying the magnitude of the dawn–dusk field with K_p. Equatorial convection paths for zero-energy particles were traced backward in time to identify regions that had been in a "closed" field-line configuration for a given number of days preceding the start of the calculations. The "open" field-line condition was taken as occurring if particle trajectories extended beyond equatorial distances of 10 R_E. The time of closure or time to the last preceding condition of open field lines was considered a measure of the local density level. It was found possible to model an initial set of OGO-5 observations in terms of the passage of the satellite through a tail-like extension of the main body of the plasmasphere.

A challenging current problem is the interpretation of the fine structure of outlying regions (scale sizes <1 R_E) reported, for example, by Chappell (1974) and Maynard and Chen (1975). Maynard and Chen (1975) found that while a convection model of the type described above can predict the general location of outlying structure observed near 5 R_E (apogee) from Explorer 45, additional, localized loss processes must be invoked in order to explain the limited extent and irregularity of some of the density features. In further study, Chen and Grebowsky (1976) found that fine structure of the plasmasphere boundary of scale size <1 R_E can be predicted if random spatial variations of order 0.1 R_E in scale are combined with large scale electric fields of the type previously used. The fine structure preferentially develops in the dusk sector, where minimum flow speeds are found. Barfield *et al.* (1974) suggested that an example of an apparently detached plasma region observed from Explorer 45 during an early phase of a magnetic storm may be explained in terms of localized depletion of the thermal plasma in a duskside plasma region that was penetrated by the plasma sheet. The localized depletion, reconfigured by convection electric fields during substorms, would be observed as a density trough separating the detached region from the main plasmasphere.

Whistlers have long been used to study magnetospheric plasma density (e.g. Corcuff, 1975; Brice and Smith, 1971); the method provides determinations of magnetospheric plasma density independent of those obtained from the ion mass spectrometer on OGO 5 (Harris and Sharp, 1969) and from the E-field probe on Explorer 45 (Maynard and Cauffman, 1973). The purposes of this brief report are to show how examples of outlying structure appear in whistler data and to provide limited information on the morphology, duration and apparent motion of the structures. The data are limited to equatorial geocentric distances of $\simeq$3–6 R_E, less than typical distances to the outlying regions observed from OGO 5 (Chappell, 1974). The results of the research support a number of the findings of the satellite experimenters and also provide several new insights. In particular, the data suggest that the more commonly observed types of outlying high-density region in the range $4<L<5$ are attached to the main body of the plasmasphere.

DESCRIPTION OF THE EXPERIMENT

The broadband whistler data used in this research were recorded at Eights, Antarctica (75°S, 77°W, $L\simeq4$) and at Byrd, Antarctica (80°S, 120°W, $L\simeq7$) during 1965 and at Byrd in 1966. The underlying approach is illustrated in Figs. 1 and 2. Figure 1, left (from Carpenter, 1970), shows the "viewing area" in the magnetospheric equatorial plane of the Eights whistler station at three successive times, t_1, t_2, t_3 near local dusk. The viewing area is a statistical concept that indicates the limits in equatorial radius and in longitude within which roughly 90% of the whistlers observed at Eights were estimated to propagate (Carpenter, 1966). The portions of this sector occupied at any given time by whistler ducts varied widely, but during the austral winter the coverage in L space was frequently sufficient to determine

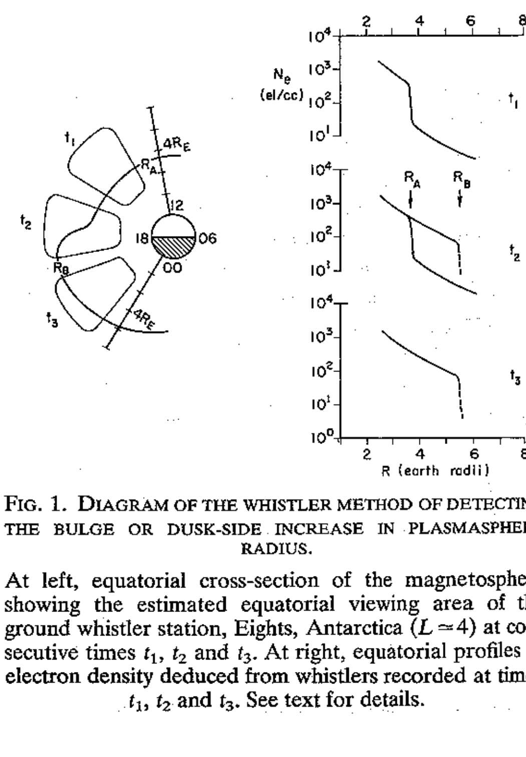

Fig. 1. Diagram of the whistler method of detecting the bulge or dusk-side increase in plasmasphere radius.

At left, equatorial cross-section of the magnetosphere showing the estimated equatorial viewing area of the ground whistler station, Eights, Antarctica ($L\simeq4$) at consecutive times t_1, t_2 and t_3. At right, equatorial profiles of electron density deduced from whistlers recorded at times t_1, t_2 and t_3. See text for details.

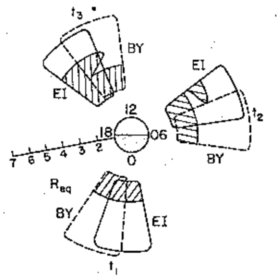

FIG. 2. DIAGRAM OF THE DETECTION OF OUTLYING PLASMA-DENSITY STRUCTURE BY A SCANNING PROCESS INVOLVING THE TWO WHISTLER STATIONS EIGHTS AND BYRD, ANTARCTICA.

The estimated magnetospheric equatorial viewing areas of the two stations at three successive times t_1, t_2 and t_3 are illustrated. The shaded areas are estimates of the shape of outlying structure detected on 11 May 1965.

equatorial density profiles of the kind illustrated schematically at the right of Fig. 1. In the profile analysis, path longitude is not explicitly resolved, but an average profile for the viewing area may frequently be defined if longitudinal density variations are not large. At time t_1 the plasmapause is at an equatorial distance R_A. Time t_2 is one of transition near which, given a spread of whistler paths in longitude, the inferred profile becomes double valued between R_A, the afternoon plasmapause radius, and (depending on duct distribution) some greater distance up to R_B, the radius at the bulge. At time t_3 the plasmapause is at R_B (details beyond the plasmapause were not usually well defined in this sector, except during quieting).

Much can be learned from a single station by allowing its viewing area to "scan" plasma structures whose motion departs strongly from corotation with the Earth (Carpenter, 1970). During quieting, however, the thermal plasma near $L = 4$–5 may move at close to the corotation velocity in most local time sectors. In such cases, data from stations spaced in longitude may be used to advantage. An example of the method is illustrated in Fig. 2, which shows schematically the overlapping viewing areas of Byrd (BY) and Eights (EI) at three different local times. Given a distribution of whistler paths over both viewing areas, it is possible to detect features of outlying plasma structure by a scanning process involving the two stations. A case study of this kind is discussed in the following section.

A diffusive-equilibrium model of the distribution of the thermal plasma along geomagnetic field lines (formulas of Park, 1972) was used in all the reported calculations of equatorial electron density from whistler data. Such a model is considered appropriate for most plasmasphere analyses (e.g. Angerami, 1970); a more rapidly varying model is recommended for study of the region beyond the plasmasphere during conditions of moderate to severe disturbance (Angerami and Carpenter, 1966). However, the reported observations occurred during conditions of quieting; substantial recovery from minimum plasma-trough levels had evidently occurred. Uncertainty in the reported density values due to both measurement and theoretical error is estimated to be of order ±20% in the higher-density regions and ±50% in the "trough-like" regions.

EXPERIMENTAL RESULTS

Two-station analysis of a taillike feature

Whistlers recorded during deep quieting following disturbance are particularly useful in studying outlying density structures that move at approximately the angular velocity of the Earth. If quieting begins as a ground station approaches the bulge, that is, if the ground station and bulge are related as in time t_1 of Fig. 1 (left), then the bulge or structure may begin to move in the direction of the Earth's rotation and may not be "overtaken" by the ground station, at least until some time after 18 MLT (Carpenter, 1970). An example of this effect, involving an apparently taillike structure of the outlying plasma, is illustrated in the two-station analysis summarized in Figs. 2 and 3. The overlapping viewing areas of the two stations are shown at three times 04, 12 and 20 UT (labeled t_1, t_2 and t_3 in Fig. 2) on 11 May 1965, a day of deep quieting following moderate magnetic disturbance. The $\sum K_p$ values for 9, 10 and 11 May were 18, 14 and 3.

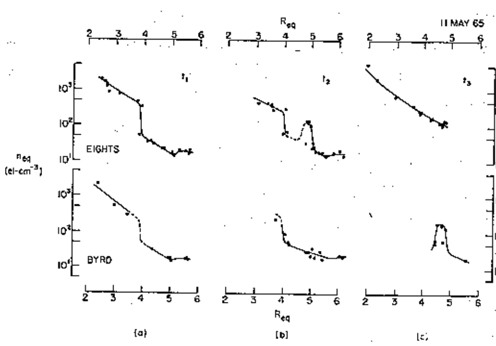

FIG. 3. MAGNETOSPHERIC EQUATORIAL PROFILES OF ELECTRON DENSITY DEDUCED FROM WHISTLERS RECORDED AT EIGHTS AND BYRD, ANTARCTICA AT THE TIMES t_1, t_2 AND t_3 INDICATED IN FIG. 2.

The profiles suggest detection of a taillike structure in the manner indicated by shading in Fig. 2.

Broadband whistlers were recorded for 1 min every 15 min at the two stations throughout the approximately 16 hr separating t_1 and t_3. Representative equatorial density profiles deduced from whistlers at times t_1, t_2 and t_3 are shown in Fig. 3. The upper profiles are from Eights data; the lower from Byrd records. Solid curves show the average trends in the profiles. Dashed portions of the curves indicate regions of less certainty. Scatter in the data points is believed to represent real fine structure in the plasma and also the effect of the distribution of the whistler paths over a range of longitudes. Hundreds of whistlers containing similar information on the profiles were observed at times near to and intermediate to the times illustrated. Many of these whistlers were scaled; the results are consistent with the profiles shown and with relatively smooth transitions between them.

The shaded areas in Fig. 2 show a simple interpretation of Fig. 3 in terms of density structure. At time t_1 both Byrd and Eights were viewing a plasmapause near 4 R_E. The plasmasphere density near $L = 3.5$ was less by a factor of $\simeq 2$ at Byrd than at Eights (Fig. 3a); this difference is consistent with the type of density structure observed in the outer plasmasphere following disturbances (Park and Carpenter, 1970).

In Figs. 3(a) and (b) the density profiles show a slight increase at 5–6 R_E. This feature was observed for many hours; it has not yet been studied in detail.

By time t_2 Eights had overtaken a region of outlying plasma that was apparently separated from the main plasmasphere by a region of reduced density. At t_1 and t_2 the density levels just beyond the plasmapause detected from both Eights and Byrd were a factor of 5–10 higher than those characteristic of relatively disturbed times (see Angerami and Carpenter, 1966). The observed densities represent a partially recovered state of the plasma (see Park, 1974; Chappell, 1972; Corcuff *et al.*, 1972), which is in fact the most commonly observed state (Carpenter and Park, 1973).

At time t_2 Byrd did not detect the outlying high density region, but continued to observe the plasmapause and low-density region beyond. In the afternoon sector at time t_3, Eights apparently moved past the outlying structure to the extent that it observed plasmasphere levels to roughly 5 R_E while continuing to observe a narrow region of low density near 4 R_E (not represented in the profile of Fig. 3c). Meanwhile, Byrd began to observe the outlying region.

The structural features "observed" at t_3 appeared to remain in the view of the stations for the following 6 hr. However, near 21 MLT ($\simeq$02 UT), when there was also a slight increase in worldwide magnetic activity, the narrow trough region "disappeared" from the view of Eights Station and only plasmasphere level densities were observed near 4 R_E. Byrd data were not well defined at this time.

Overall, the data suggest that prior to 11 May, a taillike structure developed in the dusk sector, and that during the several hours of deep quieting preceding t_1 the structure had begun to move, approximately with the Earth, across the nightside. Meanwhile, Eights and Byrd, which had been observing the plasmapause at $L \simeq 4$ on the previous afternoon, observed essentially that same profile at t_1 because of the deep quieting and the associated nearly corotational motion of the plasma. Small departures from corotation between t_1 and t_3 are evident in the apparent overtaking of the outlying structure by the stations. Departures of this magnitude are to be expected even in the quietest times. Whistler observations on exceptionally quiet days reveal several-hour-long cross-L drifts near 4 R_E which may be of dynamo origin (Carpenter and Seely, 1976). The observed flow speeds correspond to about 10% of the corotation velocity at 4 R_E; east–west flow activity at comparable speeds could account for the overtaking.

In Fig. 3(b) the peak density level in the outlying region observed from Eights is near a relatively smooth extrapolation of the inner plasmasphere profile. Effects of this kind were noted by Chappell (1974) and were used to infer the plasmaspheric origin of the outlying regions observed.

Single-station analysis of a tail-like feature

A case study of an outlying high-density region observed from a single whistler station (Eights) is illustrated in Figs. 4 and 5. The period was 26 March 1965, 15–23 UT, a time of reduced but continuing magnetic agitation following magnetic disturbance. On 24, 25 and 26 March, K_p (omitting subscripts) was 12344222, 23542242 and 43422222. In Fig. 4(a) are shown smoothed versions of the equatorial density profiles measured on the dayside of the Earth in the local time intervals identified as 1, 2 and 3 in Fig. 4(b). At time 1, near 11 MLT, inner and outer plasmaspheric regions are apparently separated by a trough-like region that is lower in density by a factor of from 3 to 5. The approximate width of this trough is indicated by the sketch for time 1 in Fig. 4(b). At times 2 and 3, in the mid and late afternoon, the profile continued to show approximately the same density levels in the

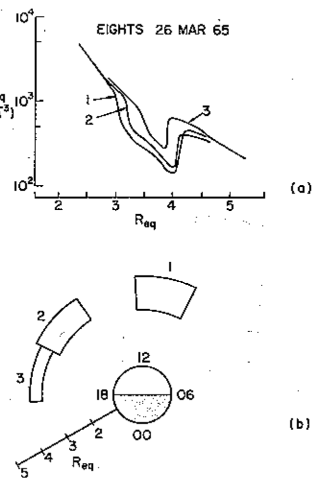

FIG. 4. SUMMARY OF OBSERVATIONS FROM EIGHTS, ANTARCTICA OF A TROUGH-LIKE DENSITY REGION SEPARATING INNER AND OUTER PLASMASPHERIC REGIONS. (a) EQUATORIAL ELECTRON-DENSITY PROFILES OBSERVED IN LOCAL-TIME INTERVALS 1, 2 AND 3 OF PART (b). (b) APPROXIMATE EQUATORIAL WIDTHS OF THE TROUGH-LIKE REGIONS AT THREE LOCAL TIMES.

outer and inner regions, but the trough became narrower and the minimum density increased. Figure 5 shows examples of profile data obtained during the three roughly 40-min intervals indicated in Fig. 4(b). The solid curves represent the general trends of the data. A few points well away from the curve may (as in the previous case) reflect fine structure in the radial profile as well as effects of the longitudinal extent of the station's viewing area.

Details of the development of the observed structure are not known, although limited whistler evidence from the nightside period that preceded the time of Figs. 4 and 5 indicates the occurrence of substorm-associated cross-L inward drifts in the outer plasmasphere near local midnight. This drift activity, if localized in longitude as previous work suggests (e.g. Park and Carpenter, 1970; Carpenter *et al.*, 1972), and followed as it was by abrupt quieting (K_p drop from 4 to 2), could have been a major factor in the development of the structure observed later on the dayside.

The apparent narrowing of the trough with time (Fig. 4) suggests that the ground station was "overtaking" the outlying structure in a manner similar to that implied in the case of Figs 2 and 3. In this case, however, the magnetic quieting was not nearly as deep, and possibly in consequence, the relative motion of the station and structure was apparently faster. It is inferred that the trough disappeared from the station's view near 18 MLT, although the data were not sufficient to describe this effect in detail.

A narrow nightside trough observed during deep quieting

Figure 6 shows a narrow trough observed from Byrd, Antarctica whistlers on 29 August 1966, 1150–1235 UT (≈06 MLT). The period was one of deep quieting ($K_p = 0$–1) following a weak magnetic disturbance ($K_p = 2$). The K_p values (subscripts omitted) for 28 and 29 August were 10111222 and 10014235. The data show that the trough was at approximately the position indicated for a ≈12 hr period extending from pre-midnight to post-dawn. After this period the data were not well defined.

The trough is relatively narrow and appears at ≈5 R_E, a distance greater than that of the trough of Fig. 3. The larger distance may be a consequence of the relatively low level of disturbance preceding the observations. The outlying densities are at a level consistent with an extension of the plasmasphere profile. The case of Fig. 6 may be an example of the type of trough structure reported by Taylor *et al.* (1971), who from OGO-4 polar orbiting satellite data showed light ion profiles near 900 km following magnetic disturbances in September 1967. They reported on the nightside a deep H^+ trough which was only a few degrees wide and was

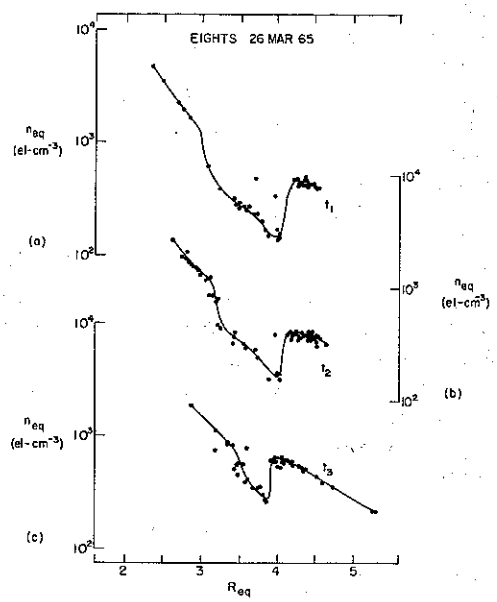

FIG. 5. EQUATORIAL ELECTRON-DENSITY MEASUREMENTS FROM EIGHTS, ANTARCTICA USED AS THE BASIS FOR THE SUMMARY IN FIG. 4.

Data points from whistlers recorded at various times within an indicated time interval have been combined.

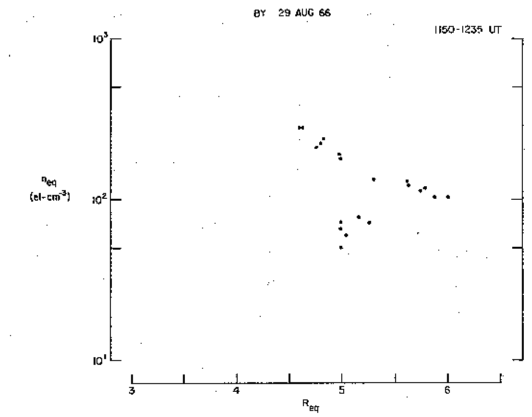

Fig. 6. Equatorial profile of electron density obtained from whistlers recorded at Byrd, Antarctica during a 45-min period on 29 August 1966, showing evidence of a narrow region of reduced density near 5 R_E.

observed to persist for at least a number of hours. The trough was interpreted as separating the main plasmasphere from a coroting tail-like plasmaspheric region.

Additional results

In several previously reported bulge encounters of the type illustrated in Fig. 1, a trough-like region at radius R_A was found to penetrate eastward into the bulge region, that is, reduced densities at radius R_A were observed several hours after the bulge encounter at time t_2 (Carpenter, 1970). As in the cases of Figs. 2 and 5 above, the "disappearance" of such regions and the subsequent observation of higher densities at the same radii suggest that tail-like structures were being scanned.

If many of the outlying regions observed by whistlers were "detached" from the main plasmasphere, some observed profiles might appear as in Fig. 3, upper panels (a) and (b), but in time sequence from (a) to (b) to (a). While properly detailed studies remain to be made, surveys of data from approximately 300 austral winter days have not revealed clear evidence of such effects in the approximately 3–6 R_E viewing range of the ground stations.

CONCLUDING REMARKS

The reported case studies support satellite results by showing structures at 3–6 R_E separated from the main plasmasphere by trough-like depressions ranging in width from about 0.2 to 1 R_E. The cases represent conditions of quieting. The densities within the outlying structures are at levels consistent with outward extrapolations of plasmasphere profiles. The densities in the trough-like regions are consistent with previous observations of recovery states in the plasma trough region. The structures can evidently be long-enduring, having been observed from slowly "scanning" ground stations for periods of order 12 hr. The relative east–west motion of ground stations and plasmasphere structure at $L \approx 4$–5 ranges from above the Earth's angular velocity during disturbed periods (as in bulge encounters) to an order of 10% of the Earth's angular velocity on the quietest days (case of 11 May 1965). The quiet day motions are probably of dynamo origin.

The cases occurring during deep quieting (11 May 1965 and 29 August 1966) suggest the approximate rotation with the Earth of structure formed during previous moderate disturbance activity in the dusk sector. The case of 26 March 1965 may represent a structure formed near local midnight.

The outlying structures reported here appear to be closely related to the bulge phenomenon. In general the data support other experimental and theoretical evidence that the dusk sector is one of major importance in the generation of outlying density structure. While relatively few cases have been studied, our tentative conclusion is that irregularities of the type reported here regularly develop near 4–5 R_E during moderate substorm activity.

This research suggests that at least a major class of the structures developed near 4 R_E are taillike in nature, joined to the main body of the plasmasphere. In contrast, OGO-5 data have been interpreted as showing regions of detached plasma beyond 5 R_E (Chappell, 1974). The difference may be related to the pronounced spatial structure of electric fields and associated plasma bulk flows observed in high latitude ionospheric regions that are conjugate to the magnetospheric regions in which the OGO-5 observations were made (e.g. Gurnett and Frank, 1973). Chappell (1974) has discussed this electric field structure as a probable factor in the origin of the detached regions.

It is possible that on auroral and near-auroral field lines there are ionosphere-magnetosphere coupling processes that give rise to enhanced magnetospheric densities. The leveling off of the density profiles in Fig. 3 near 5.5–6 R_E may indicate an enduring nightside feature of this sort. Chappell (1974) suggested the possibility that detached plasma regions observed from OGO 5 near the dayside magnetopause may be associated with the magnetopause and its structure.

The further study of the physics of outlying structures is a major objective of whistler experimenters using spaced station techniques and vlf direction finding methods. It should be possible to extend the analyses to regions beyond 5 R_E particularly during local afternoon, when ducted propagation to relatively high latitudes is known to occur (Carpenter, 1963).

The long persistence and relatively slow east–west motion of outlying structure during quieting suggest that such regions may be particularly favourable for future experiments in which plasma gradients are needed, minimal disturbance activity is desired, and in which observability from ground stations is important.

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