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Multi-Experiment Detection of the Plasmapause from EOGO Satellites and Antarctic Ground Stations

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Three independent methods of detecting the plasmapause have been compared: (1) the GSFC ion mass spectrometers on OGO 1 and OGO 3; (2) Stanford University/Stanford Research Institute broadband VLF receivers (0.3–12.5 kHz) on OGO 1 and OGO 3; (3) Stanford University broadband VLF receivers at ground stations Eights and Byrd, Antarctica, near the 90°W meridian. In the satellite VLF data the plasmapause crossings are identified by abrupt changes in observed whistler and VLF noise activity and by noise bands of limited duration. In two cases of simultaneous VLF and ion data from the same EOGO satellite, plasmapause crossings were detected by both experiments within less than 0.1 R_E in L value. In eight cases of OGO 1 ion data and simultaneous ground whistler data spaced from 1 to 12 hours from OGO 1 in local time, good agreement was found between the measured plasmapause positions. The comparisons provide new verification of the essentially worldwide extent of the plasmapause and also verify previous indications that the radius of the plasmapause is frequently about constant over large local-time sectors in the range 0–18 LT.

INTRODUCTION

Early emphasis in plasmapause studies has been upon plasmapause crossings, since detection of the boundary is often simpler than a description of the regions on either side. Many boundary crossings have been identified in satellite data, including results from ion mass spectrometers on OGO 1 and 3 [*Taylor et al.*, 1965; *Taylor et al.*, 1968; *Brinton et al.*, 1968], Faraday cups on IMP 2 [*Binsack*, 1967] and on OGO 1 and 3 [*Vasyliunas*, 1968], and traps on Electron 2 and 4 [*Bezrukikh*, 1968]. The reported plasmapause position measurements agree statistically both among themselves and with ground-based whistler measurements of the plasmapause radius [*Carpenter*, 1966, 1967].

In spite of the extent of this work, the plasmapause remains a phenomenon of great mystery both in matters of detail and of large-scale structure. The vast size of the plasmasphere and the apparent abruptness of plasma density variations at the boundary suggest that further work include correlation studies, so as not only to provide new descriptive information, but also to encourage development of new detection schemes and provide means of verifying the interpretation previously placed on data from individual experiments.

A recent correlation study showed close agreement between VLF data on plasmapause crossings from the Alouette 1 and 2 satellites and ground-based whistler measurements of the plasmapause radius [*Carpenter et al.*, 1968]. On the satellites the plasmapause was detected as an abrupt termination or sudden decrease in the rate of whistlers propagating from the conjugate hemisphere. Accompanying this whistler cutoff there was frequently a sudden breakup in the VLF noise called the lower hybrid resonance (LHR) noise band.

The purpose of the present paper is to describe another correlation study of plasmapause position, this time involving various combinations of three independent experiments (1) the GSFC ion mass spectrometers on OGO 1 and OGO 3; (2) the Stanford University/Stanford Research Institute broadband VLF receivers (0.3–12.5 kHz) on OGO 1 and OGO 3; (3) Stanford University broadband VLF recordings at ground stations Eights and Byrd, Antarctica, near the 90°W meridian. Two basic types of comparison have been made, involving either: (1) ion and VLF data recorded simultaneously at high altitudes on the same OGO satellite or (2) OGO 1 ion data and simultaneous whistler ground data spaced 1 to 12 hours from OGO in local time.

In the ion mass spectrometer data, the plasmapause is identified by characteristic large decreases in the ion currents of H^+ and He^+. Examples of plasma density profiles deduced from the ion currents have been shown by *Taylor et al.* [1965, 1968], and by *Brinton et al.* [1968]. In the ground VLF data the plasmapause and its approximate position in space are identified from the dispersion characteristics of multicomponent whistlers in the manner described by *Carpenter* [1963, 1966] and by *Angerami and Carpenter* [1966]. In the broadband VLF data recorded on OGO 1 and OGO 3, plasmapause crossings are identified by abrupt changes in observed whistler and VLF noise activity and by noise bands of limited duration. These effects, although different in matters of detail, appear closely related to some of the low-altitude crossing phenomena detected on Alouette 1 and 2 [*Carpenter et al.*, 1968].

Three purposes of the present note are (1) to illustrate the VLF method of detecting plasmapause crossings at high altitudes; (2) to show two cases of close agreement between the VLF and ion mass spectrometer methods of detecting the plasmapause; and (3) to demonstrate through local-time separation of simultaneous measurements the essentially worldwide longitudinal extent of the plasmapause.

The data described below were selected on the basis of availability and suitability for comparison. There are seven cases from May to June 1965, involving OGO 1, and one case for July 1966, involving OGO 3. The supporting ground whistler data were obtained from Eights station (64°S geomagnetic latitude) and Byrd station (71°S geomagnetic latitude) in Antarctica.

SIMULTANEOUS DETECTION OF THE PLASMAPAUSE BY TWO EXPERIMENTS ON THE SAME EOGO SATELLITE

Figures 1 and 2 illustrate simultaneous detection of the plasmapause from the EOGO satellites by an ion mass spectrometer and broadband VLF receiver. Figure 1 represents the OGO 3 outbound pass of July 5, 1966, and Figure 2 the inbound OGO 1 pass of June 9, 1965. In both figures the satellite orbit is projected on a geomagnetic meridian plane. The solid and dashed portions of the curves represent satellite positions inside and outside the plasmasphere, respectively, as determined from the two experiments. Ion concentration as determined from the mass spectrometer (by the GSFC group) is plotted versus time and is to be compared with the VLF spectra recorded simultaneously. In Figure 3 the sections of VLF data marked *A* through *F* in Figures 1 and 2 are shown on an expanded time scale.

Details of the July 5, 1966, event (Figure 1). On the OGO 3 outbound pass of July 5, 1966, a plasmapause crossing was identified in the ion data at approximately 1250 UT, at which time the concentration of H^+ was observed to decrease rapidly by about an order of magnitude. At this time the satellite was in the afternoon sector at ~1640 LT, a geomagnetic latitude of 30°N and dipole $L = 4.6$ (see also Figure 5, lower left). The period was one of low to moderate magnetic agitation, with maximum *Kp* values in the preceding 12 and 24 hours of 2+ and 4+, respectively. Arrows on the satellite trajectory identify the boundary crossing and indicate a spatial range of uncertainty of about 0.1 *L* in determining a point location of the plasmapause from the associated ion concentration profile. Corresponding time intervals are indicated by arrows on the VLF and ion records.

The VLF data begin in the top panel at ~1220 UT and continue outbound toward the plasmapause in the bottom panel. Within the plasmasphere there is high whistler activity and there is also a well-defined noise band in the range ~400–900 Hz. (The intense signal appearing near 12h 38m 30s and decreasing in frequency with time is interference from the magnetometer aboard the spacecraft.) After ~1235 the whistlers exhibit well-defined echoes, a phenomenon that may be dependent on the proximity of the boundary (interval *A* is shown expanded in Figure 3*A*). After ~1245, the whistler activity diminishes in intensity, and at 12h 47m 50s UT, within roughly two minutes of the time of plasmapause crossing indicated in the ion data, there appear two band-limited noises with center frequencies 3.7 and 4.7 kHz (only the lower one is shown in Figure 3*B* so as to avoid AGC effects on the analysis by the magnetometer signal). The onset of the noise bands is quite sudden and can be resolved within 10 seconds (cf. Figure 3*B*). At ~1249 the ion data indicate the beginning of a plasmapause profile. At about this time the noise bands at 3.7 and 4.7 kHz decay, and at ~1250, faint whistler activity and the 400–900 Hz noise cease to be detected. The behavior of the 400–900 Hz band is consistent with reports on magnetic field measurements in the 0–1000 Hz range on OGO 1 by *Russell et al.* [1968].

At the approximate time of the OGO 3 observations summarized in Figure 1, ground-based whistler data on the plasmapause radius were obtained at Byrd Station, Antarctica. When OGO 3 crossed the plasmapause at about 1640 LT, Byrd Station was 'viewing' a region of the magnetosphere in the local time sector ~0600–0700 (see Figure 5, lower left). The radius measured from Byrd data was in the range 4.6–5.6 R_E, in good agreement with the crossing value of $L = 4.6$ found by OGO 3. Certain longitudinal and local-time differences in plasmapause radius are to be expected, and further details of this comparison will be presented in a later paragraph.

Details of the June 9, 1965, event (Figure 2). The ion and VLF data observed on the OGO 1 inbound pass of June 9, 1965, are shown in Figure 2. The VLF data begin in the top panel at 0938 UT ($L = 4.5$) and continue inbound toward the plasmapause in the bottom panel. The ion data begin at 1004 UT, with the first detectable concentration of H^+ observed above the experimental limiting sensitivity of 1 ion/cm^3. The ion spectrometer detected the plasmapause crossing at approximately 1013 UT, at which time the satellite was in the late morning sector at ~1100 LT, geomagnetic latitude 38°S, and dipole $L = 4.02$ (see also Figure 5, upper middle). The magnetic condition was one of moderate, steady agitation, with *Kp* in the range 2–4.

Although the data of Figure 1 were obtained from a 3-axis attitude stabilized satellite, OGO 1 was spin-stabilized, and consequently the raw H^+ ion currents used for Figure 2 were modulated by the variation in angle-of-attack between the spectrometer orifice and the velocity vector. Although this modulation does not obscure the fundamental evidence of the plasmapause crossing, the modulation has been eliminated in the final data by normalizing the measurements to zero angle-of-attack using inflight calibration of the dependence of sensor efficiency upon spacecraft attitude. Subsequent conversion of ion currents to ion concentrations followed the plasma probe technique described in previous papers by *Taylor et al.* [1965] and *Brinton et al.* [1968].

In Figure 2, connected arrows again indicate the spatial range of the plasmapause, spanning the period 1009 UT ($L = 4.1$) to 1014 UT ($L = 4.0$). During this interval and earlier in the pass, the H^+ currents occasionally fell below the detectable level, so that concentrations cannot be determined. In comparing the data of Figures 1 and 2, note that differences in orbit result in differences in the time rate of change of L near the plasmapause.

In contrast to the case of Figure 1, the VLF records of Figure 2 exhibit complex noise activity outside the plasmapause. The principal crossing effect is a transition from an outer regime of intense noise activity in the range 5–8 kHz and rising noise tones near 2 kHz to an inner regime of whistler activity and diffuse noise bands in the range ~0.6–3 kHz. (The narrow vertical lines on the spectrogram represent telemetry fading at the spacecraft spin period of 12 seconds.)

Reviewing details of the VLF activity, the rising chorus tones near 2 kHz appear to increase in intensity with time, being particularly well-defined after ~0951 (upper VLF record). As the plasmapause is approached, the rising tones begin to disappear during intervals when the log compressor receiver is apparently captured by intense noise bursts near 5–6 kHz. Figure 3*C* shows details of the 1–2 kHz rising tones and also complex activity near 5 kHz at the beginning of an intense noise event.

On the upper record of Figure 2 noise activity near 5–6 kHz exhibits a succession of short bursts wth irregular structure but relatively smoothly increasing over-all frequency limits. As the plasmapause is approached, the bursts become more frequent, until at ~1004, when the first detectable ionization is encountered, there begins a prolonged band-like noise containing many closely spaced elements. At ~10h 09m 30s another long noise event begins, this time exihibiting relatively little structure (cf. Figure 3*C*). The noise band increases in intensity, and then at 10h 12m 09s UT begins a series of irregular variations in bandwidth and center frequency, finally fading away near 1015 UT. Figure 3*D* shows the band at a high intensity level near 1014 UT, only a minute before its disappearance (shown in Figure 3*E*).

A noise band of center frequency ~2 kHz appears near 1014 UT and continues after the disappearance of the higher frequency noise (cf. Figures 3*D*, 3*E*). Within a few minutes the upper part of the new band fades and the noise becomes a steady narrow band centered at ~1 kHz (Figure 3*F*).

The last detectable rising-tone emission is at 10h 14m 55s, and the first tentative evidence of a whistler is at 10h 15m 03s UT (cf. Figure 3*E*), at which point the ion concentration has significantly increased. After this time whistlers become more numerous and better defined; an example is shown in Figure 3*F* at 10h 22m 03s.

Some of the details of the VLF noise and the apparent patchiness in the ion concentration observed outside the plasmapause on this OGO 1 pass may eventually be explained by the grazing nature of the orbit and the associated encounters with boundary fine structure. Figure 5, upper middle, shows the orbit near plasmapause crossing in coordinates of *L* versus local time and indicates the rapid longitudinal variation experienced by OGO 1 as the magnetic shell parameter changed only slowly.

Ground whistler data for the June 9 OGO 1

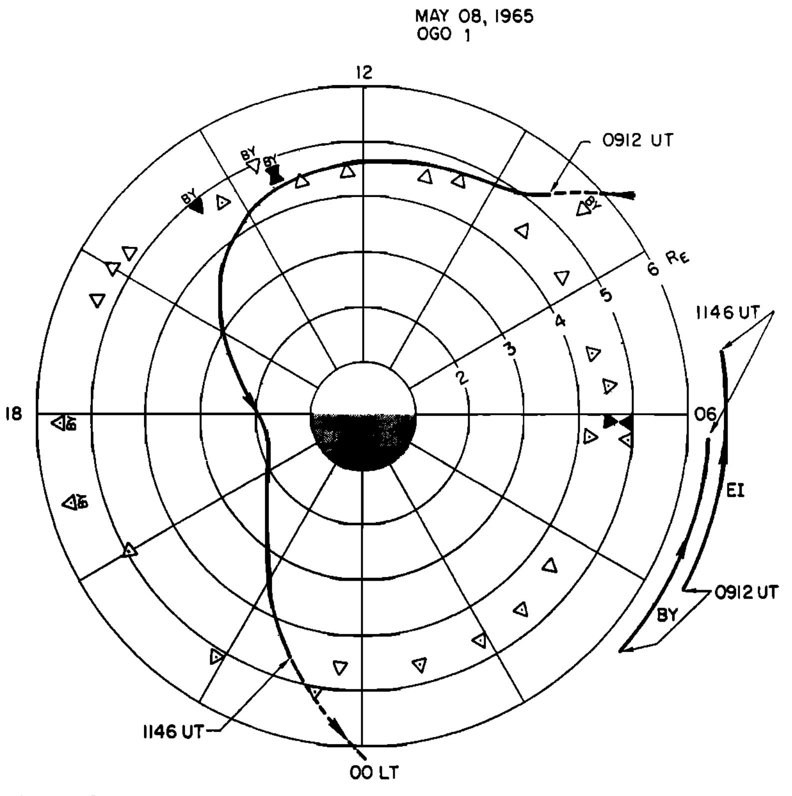


Fig. 4. Example of comparison between OGO 1 ion data and ground whistler data on the plasmapause position. The OGO 1 orbit of May 8, 1965, is projected in coordinates of *L* value versus local time. Triangles represent ground whistler information on plasmapause radius, whereas the transition from dashed to solid curve indicates a plasmapause crossing in the ion data. During the 2½ hours of the OGO 1 passage through the plasmasphere, the ground stations Eights and Byrd moved through the arcs of circles indicated near the 05–06 LT meridians. Further details of the comparison and meaning of symbols are given in the text.

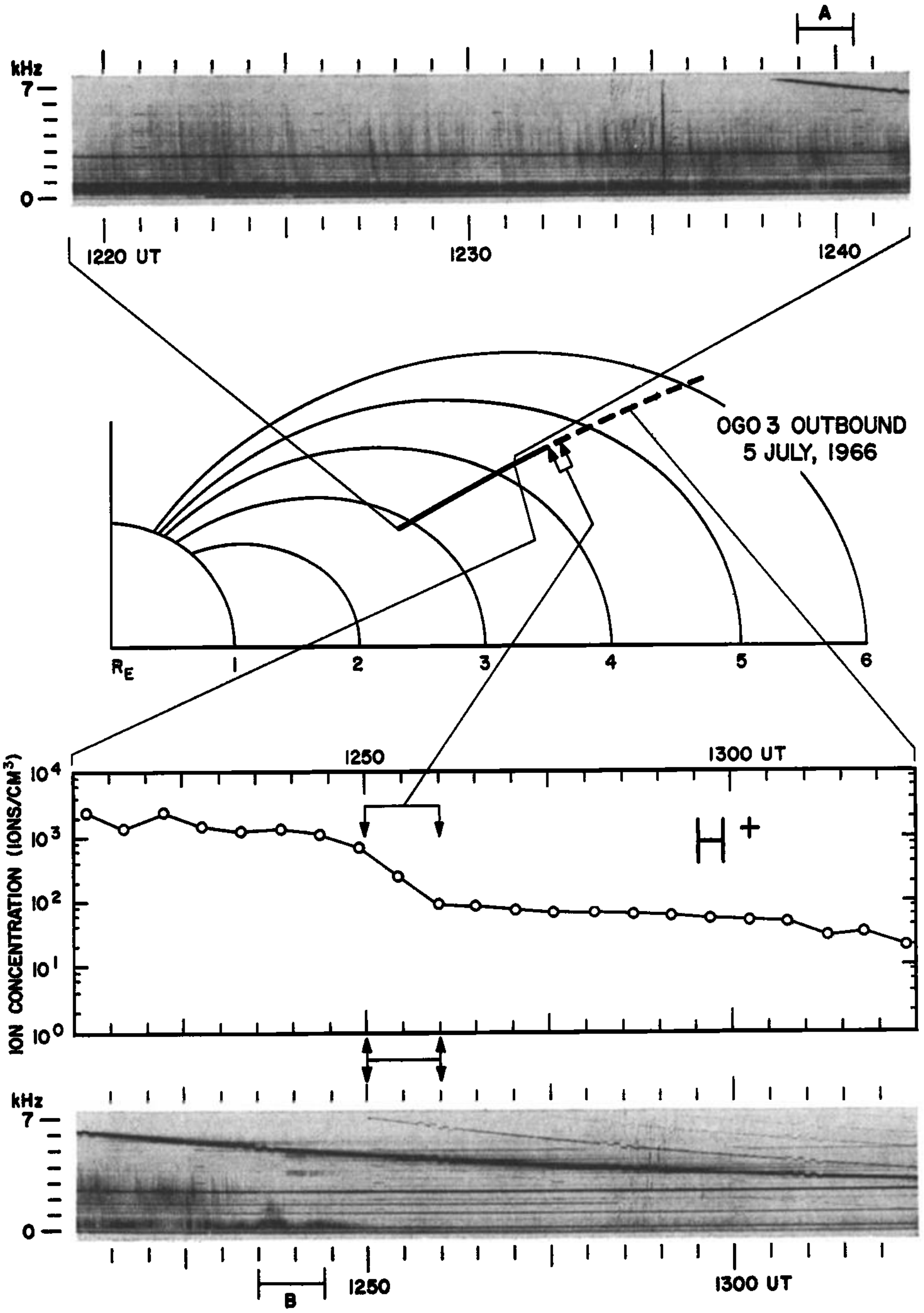


Fig. 1. Comparison of simultaneous VLF and ion mass spectrometer data on a plasmapause crossing during the OGO 3 outbound pass of July 5, 1966. The satellite orbit is shown in a geomagnetic meridian projection. A pair of arrows along the orbit indicates the position of the plasmapause as detected in the ion data. The corresponding time interval is shown by arrows on the ion and VLF records. The VLF data begin in the top panel and continue outbound toward the plasmapause in the bottom panel. Horizontal lines on the records are of instrumental origin. The VLF signal descending in frequency after 12h 38m 30s is interference from the on-board magnetometer.

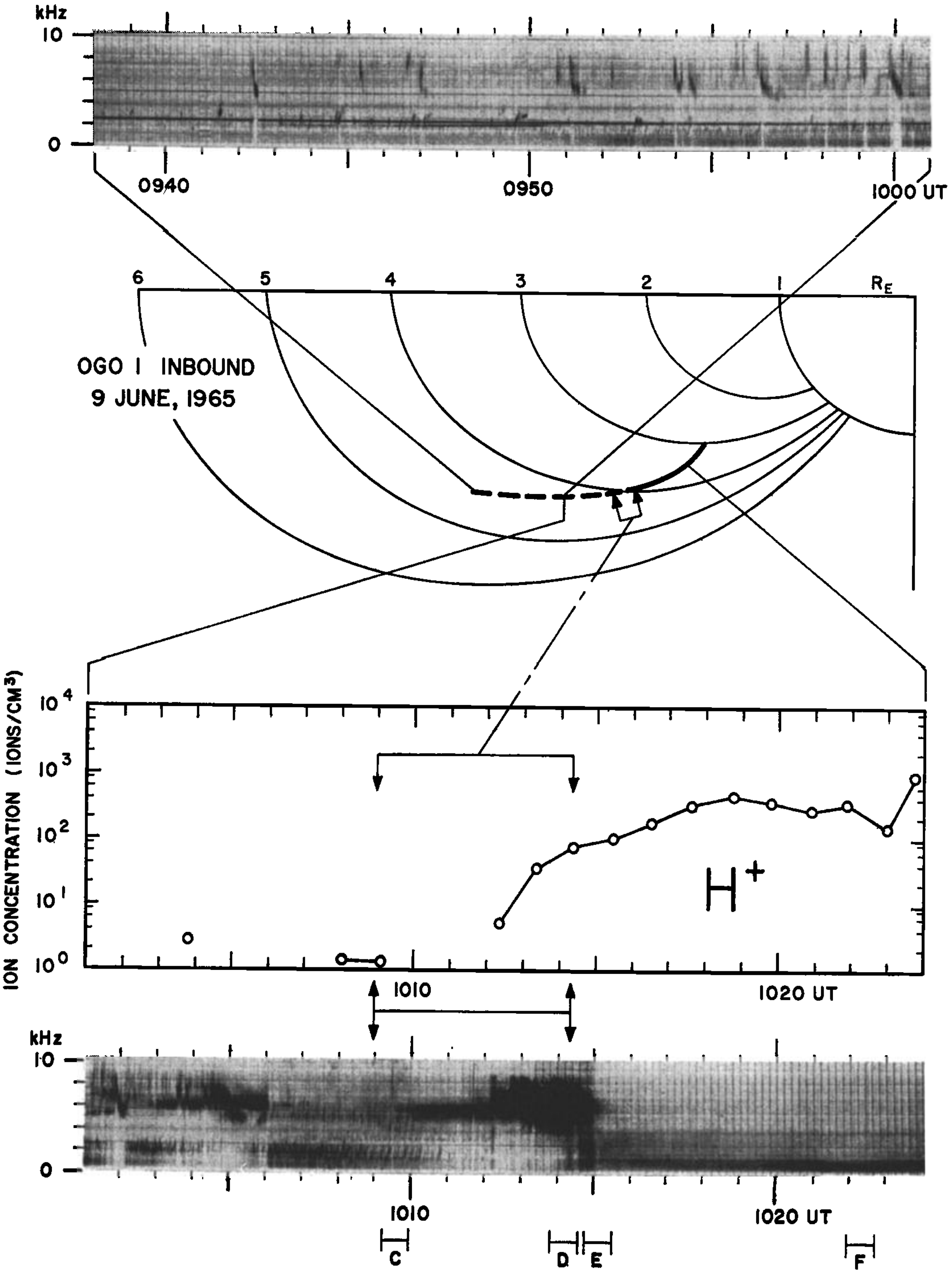


Fig. 2. Comparison of simultaneous VLF and ion mass spectrometer data on a plasmapause crossing during the OGO 1 inbound pass on June 9, 1965. A pair of arrows along the orbit indicate the position of the plasmapause as detected in the ion data. The corresponding time interval is shown by arrows on the ion and VLF records. The VLF data begin in the upper record and continue inbound toward the plasmapause on the bottom panel.

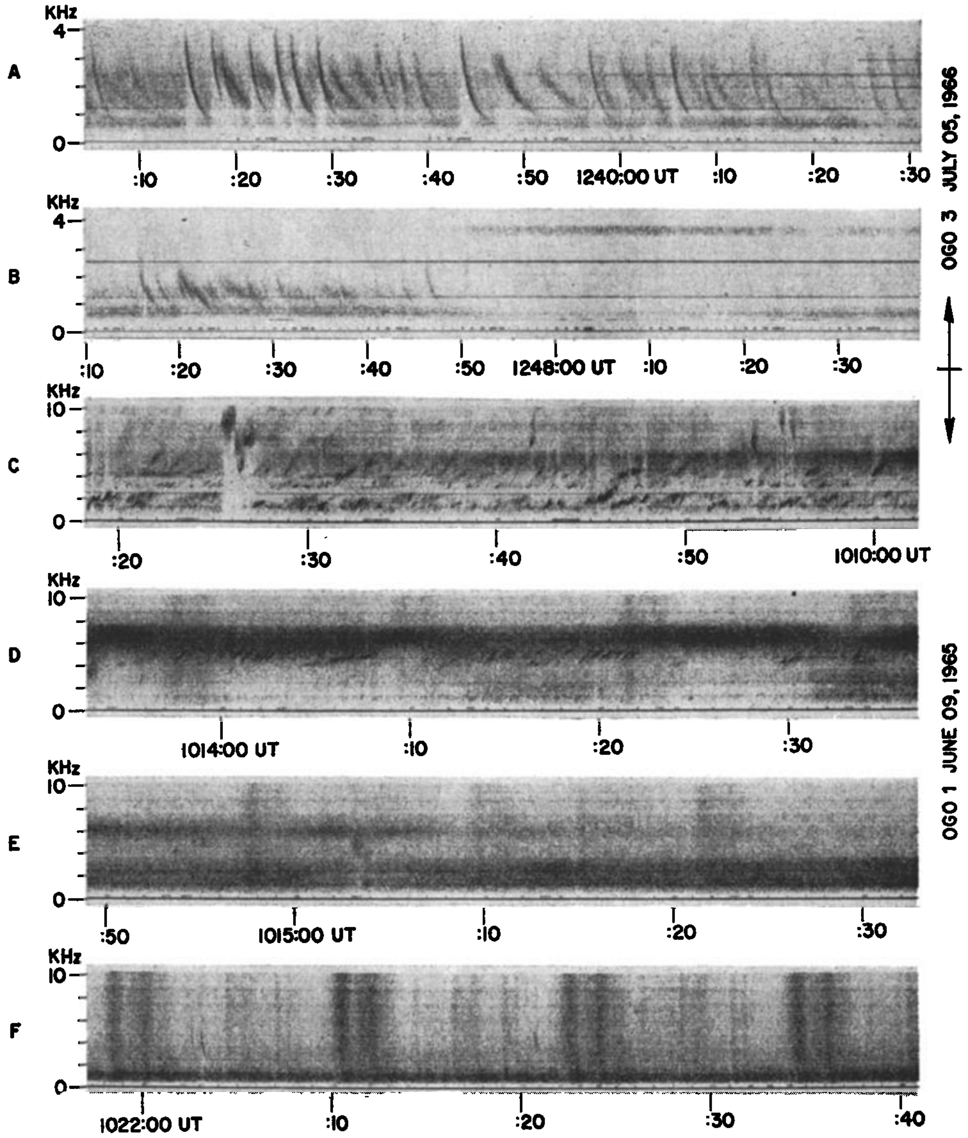


Fig. 3. Expanded VLF spectra for intervals marked *A* and *B* in Figure 1 and *C* through *F* in Figure 2. The frequency scale of panels *A* and *B* is 0-4 kHz, instead of 0-7 kHz as in Figure 1.

pass were obtained at Eights Station, Antarctica. The plasmapause radius as determined from Eights data for 1230–1300 UT (about 0730–0830 LT) was in the range $L = 3.8$–4.1, and again there is good agreement with the OGO 1 value ($L \sim 4$, ~1100 LT). The comparison is discussed further in a later section.

COMPARISON OF GROUND AND SATELLITE MEASUREMENTS OF THE PLASMAPAUSE POSITION

A comparison of OGO 1 ion data on plasmapause crossings and ground data on the plasmapause radius is illustrated in Figure 4. The satellite orbit is presented in coordinates of *L* value versus local time, and plasmapause crossings are again shown by the transition from solid to dashed curves.

The combination of a fixed ground station and a satellite in nonsynchronous orbit affords the opportunity for (1) simultaneous measurements at various local time spacings, and (2) nearly simultaneous measurements in which the ground data are plotted as a function of local time before and after the plasmapause crossings by the satellite. In the case illustrated in Figure 4, the diurnal variation of the plasmapause position deduced from whistlers recorded at Eights and Byrd Stations on May 8, 1965, is plotted with two OGO 1 crossings of the plasmapause on the same day.

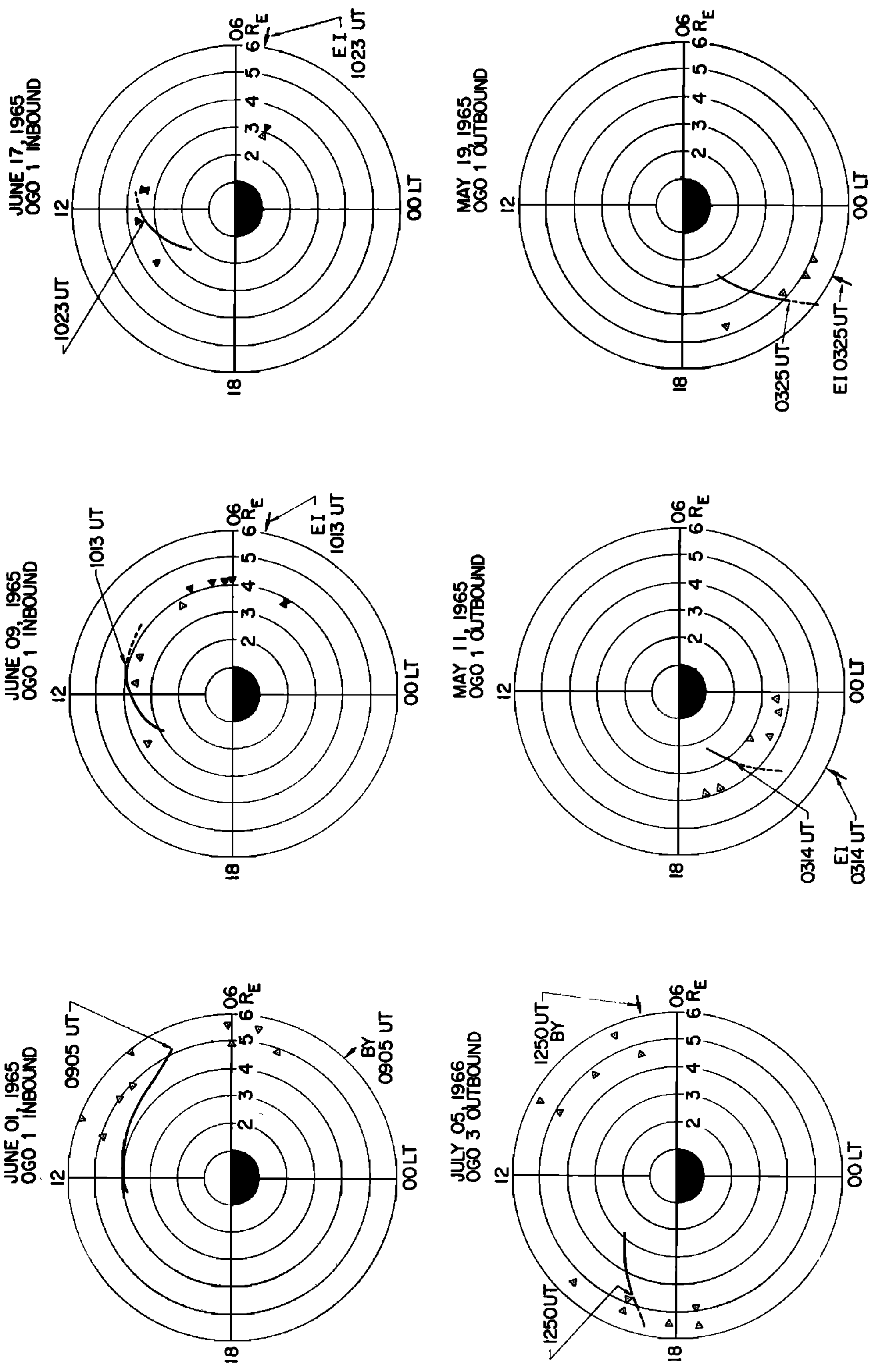
Ground whistler data on the equatorial radius of the plasmapause are represented by triangles. The value of equatorial radius was calculated assuming propagation in a centered dipole geometry. A triangle with apex pointing toward the earth represents a whistler component that propagated in the tenuous region outside and near the plasmapause, whereas a triangle with apex pointing away from the earth is interpreted as having propagated inside and near the boundary. The filled triangles represent cases in which the plasmapause is known to be within about 0.2 L in the direction of the apex. The open triangles represent cases of less certainty in which the plasmapause is interpreted as lying within about 0.5 L in the direction of the apex. (The use of whistler data in which propagation is detected on only one side of the plasmapause has been discussed in a previous paper [*Carpenter*, 1966]. When suitable caution is observed, such as by using periods preceded and followed by more complete data, and by restriction to periods of high whistler activity, the method has been found to be very useful in plasmapause studies.)

In considering the details of Figure 4 the ground measurements may be thought of as made by two closely spaced 'synchronous' satellites, corotating with the earth near the dawn meridian. Meanwhile, OGO 1 arrived at the plasmapause boundary in the forenoon sector and entered the plasmasphere at 0912 UT. At 1146 UT, about 2½ hours later, it emerged from the plasmasphere near the midnight meridian. During this interval the ground stations moved between the local times indicated by the arcs of circles, so that the whistler measurements near these arcs represent the plasmapause measurements most nearly time-coincident with those of OGO 1. The series of triangles extending back across the nightside shows in local time the measurements made at Eights and Byrd during 9 hours before the arrival of OGO 1 at the plasmapause. The series of data points across the dayside represents similar observations following the emersion of OGO 1 from the plasmasphere on the nightside.

The general appearance of Figure 4 is one of substantial agreement between the ground and satellite data. The expected worldwide extent of the plasmapause is verified by the simultaneous detection of the boundary, first with an ~04–09 LT separation (ground and satellite, respectively) and then with an ~06–23 LT comparison. The observed values of plasmapause radius in the range 4.5–5.5 R_E are consistent with expectations for the moderate level of geomagnetic agitation on May 8, 1965 ($Kp = 1\text{–}3$) [*Carpenter*, 1966; *Taylor et al.*, 1965; *Binsack*, 1967]. The asymmetry shown in the ground data (triangles), with a dawn minimum and dusk maximum in the plasmapause radius, is also in agreement with expectations from previous work [*Carpenter*, 1966].

The difference between the OGO 1 measurement of the plasmapause position at 0912 UT and the value obtained from whistlers when the ground station reached the same local-time region 5 hours later is probably explicable in terms of magnetospheric substorm activity. Substorm activity began to increase at about 0440 UT on May 8, 1965, in time to effect a decrease in the plasmapause radius near Byrd and Eights, but apparently not in time to affect the position of the boundary that was eventually crossed at 0912 UT by OGO 1. The effect on Eights' data is indicated by the inward shift of data points near 2330 LT.

Fig. 5. Comparisons of OGO 1 and OGO 3 ion data on plasmapause crossings with simultaneous ground whistler measurements of the plasmapause radius and also ground measurements in the preceding and succeeding hours. The transition from a solid to a dashed curve indicates a plasmapause crossing as identified in the ion data. An arrow along the periphery of the plot indicates the approximate region of whistler observations at the time of plasmapause crossing by the satellite.


JUNE 17, 1965
OGO 1 INBOUND
1023 UT
EI
1023 UT
JUNE 09, 1965
OGO 1 INBOUND
1013 UT
EI
1013 UT
JUNE 01, 1965
OGO 1 INBOUND
0905 UT
BY
0905 UT
MAY 19, 1965
OGO 1 OUTBOUND
0325 UT
EI 0325 UT
MAY 11, 1965
OGO 1 OUTBOUND
0314 UT
EI
0314 UT
JULY 05, 1966
OGO 3 OUTBOUND
1250 UT
1250 UT
BY
06
12
18
00 LT
2
3
4
5
6 R_E

Additional case studies. A group of six ground-satellite comparisons of the plasmapause radius is presented in Figure 5. The symbolism and coordinates are essentially the same as in Figure 4, but only single satellite crossings of the boundary are shown. An arrow along the periphery of each polar plot shows the approximate location of the ground station at the time of the plasmapause crossing by the satellite. The lower left and upper middle plots provide additional documentation on the cases illustrated in Figures 1 and 2, respectively. In the case of June 1, 1965, upper left, the boundary identification is tentative, since the ion data coverage began just beyond $L = 5$, in time to observe only part of a plasmapause-like profile.

The six cases of Figure 5 represent relatively large variations in magnetic activity, local time of plasmapause crossing by the satellite, and local-time separation of the ground and satellite measurements. Moving from left to right at the top, there is a progression from quiet magnetic conditions (June 1, 1965) to moderate disturbance (June 9, 1965) to severe disturbance (June 17, 1965), and a corresponding shrinkage is evident in the plasmapause radius. In all three cases there is good agreement between the ground and satellite data.

Moving from left to right along the top and then the bottom row of Figure 5, there is a progression in local time of satellite crossing from morning to premidnight, and also there are variations in satellite-ground separation from 1 to 10 hours. Good agreement is obtained for all the separations, indicating the essential persistence of the plasmapause over large intervals of time and space.

The number of case studies presented here was limited by several factors, including seasonal variations in ground whistler data, low-power cycles on OGO 1, and the need to compare special purpose OGO VLF data with digital data. Because of these restrictions, the results should be considered as indicative only of a class of cases, with the size of the class still unknown.

CONCLUSIONS

Within the limits of the cases illustrated thus far, it is concluded that:

(1) On two occasions of observations on an EOGO satellite, plasmapause crossings detected by VLF techniques and by an RF mass spectrometer were coincident within 0.1 L.

(2) Broadband VLF data from satellites in eccentric, equatorial orbits may on some occasions be useful in identifying the plasmapause. Significant changes in VLF activity have been observed to take place within intervals of ten seconds or less.

(3) New verification of the worldwide extent and persistence of the plasmapause has been obtained from eight cases of simultaneous satellite-ground observations. The measurements involved local-time separations ranging from 1 to 10 hours, varying levels of magnetic agitation, and varying local times of boundary crossing by the satellite.

(4) The ground-satellite measurements strongly support previous suggestions, based on measurements on a single meridian [*Carpenter*, 1966], that the radius of the plasmapause is frequently about constant over large local-time sectors in the range 0–18 LT.

The results presented above may be deceptive in their simplicity. Data not presented here indicate that the plasmapause is extremely complex, with regions of irregular behavior, periods of rapid expansion or compression, and variations in details of the plasma profile at the boundary. Further generations of correlation studies are needed to obtain a proper description of these effects.

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