Ogo 2 and 4 VLF Observations of the Asymmetric Plasmapause near the Time of SAR Arc Events

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Ogo 2 and Ogo 4 VLF data on plasmapause crossings were compared with SAR arc observations reported on September 29, 1967, and on October 31 and November 1, 1968. The positions of the plasmapause and SAR arcs were found to agree within ±1° in invariant latitude. Ogo 4 evidence from the 0900–2100 MLT (magnetic local time) plane showed that the known local-time asymmetry in plasmapause L value (evening maximum, dawn minimum) could explain some of the apparent motions of the arcs as viewed from ground stations. Some other details of the arc motions are apparently due to substorm-related convection events in the outer plasmasphere.

In recent studies a close spatial relationship has been found between the position of SAR arcs and the midlatitude electron trough in the ionosphere [*Norton and Marovich*, 1969; *Norton and Findlay*, 1969]. Other studies have indicated that the midlatitude electron trough is, at least under many circumstances, a low-altitude extension of the plasmapause in the magnetosphere [*Rycroft and Thomas*, 1970; *Rycroft and Burnell*, 1970]. The purpose of the present study is to compare the plasmapause position determined from VLF satellite data with ground observations of SAR arcs on September 29, 1967, and on October 31 and November 1, 1968. The VLF data are from the Stanford University–Stanford Research Institute broad-band VLF experiments on polar satellites Ogo 2 and 4. (Ogo 2 was placed in orbit between ~400- and 1500-km altitude on October 14, 1965; Ogo 4, between ~400- and 900-km altitude on July 28, 1967.) The study shows that under the most favorable conditions for direct comparison the plasmapause and the SAR arc were located on the same magnetic shells with an uncertainty in invariant latitude of the order of 1°. A broadly similar conclusion on the relation of the plasmapause and the SAR arc has been reached by *Chappell et al.* [1971] from thermal ion measurements on Ogo 5 near the magnetic equator at the time of the October 31–November 1, 1968, SAR arc observations.

The present study provides the first direct evidence linking SAR arc motions observed from ground stations with local-time asymmetry in the plasmapause L value. Such a relation has been suggested by *Glass et al.* [1970] and *Hoch and Smith* [1971]. (The plasmapause radius is on the average largest in the evening sector and smallest near dawn [*Carpenter*, 1966, 1970; *Taylor et al.*, 1970; *Chappell et al.*, 1970]; hence the suggestion results that apparent equatorward arc motions are due to the rotation of the ground station with respect to a rigid but asymmetric plasmapause.)

The broad-band VLF technique of detecting the plasmapause from polar orbiting satellites is in a continuing state of development. Previous correlation studies have indicated a close relation between independent ground whistler or direct probe measurements of the plasmapause and both a rapid change in the occurrence rate and spectra of whistlers propagating to the satellite from the conjugate hemisphere and an onset or sudden variation in VLF noise [*Carpenter et al.*, 1968; *Taylor et al.*, 1969].

The satellite VLF information appears most straightforwardly related to the plasmapause when the satellite is on the nightside of the earth and during periods of either increasing or prolonged disturbance. Fortunately the SAR arcs involved in this study were observed under such conditions.

September 29, 1967, measurements. On September 29, 1967, a SAR arc was observed over much of the western United States [*Hoch et al.*, 1968]. During this period Ogo 2 was in a particularly favorable position for supplying plasmapause crossing data. Three of the successive subsatellite paths over the eastern, central, and far western United States are indicated in Figure 1 on a map adapted from *Norton and Findlay* [1969]. From right to left Ogo 2 crossed 50° invariant latitude (the approximate arc latitude) at 1004, 1149, and 1334 UT. The curve marked 0908 shows an Alouette 2 subsatellite path, and the curve marked 0905 shows the approximate position of the SAR arc at 0905 UT. The arc as observed from Fritz Peak (marked F in the figure) moved only slightly from 0905 until its last appearance at 1125 UT, about 25 min before the 1149 pass of Ogo 2.

The VLF spectra for the three passes shown in Figure 1 and a subsequent pass over Alaska are shown in Figure 2 in coordinates of frequency 0–10 kHz versus invariant latitude. The records are aligned vertically with respect to the time of crossing of 50° invariant latitude (thin vertical line). Listed in the figure legend are the telemetry station, approximate universal time, invariant longitude [*Evans et al.*, 1969], satellite altitude, and magnetic local time at the time of crossing 50° invariant

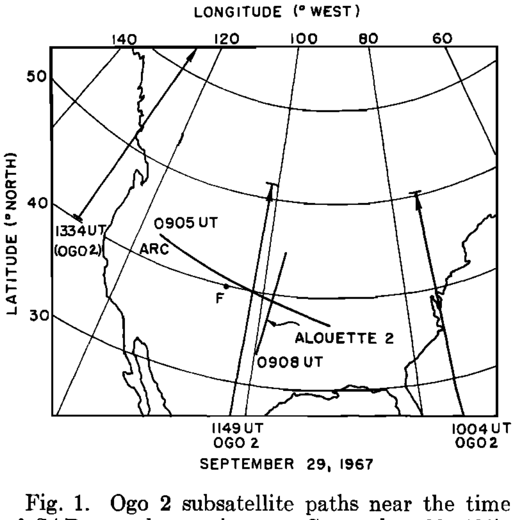

Fig. 1. Ogo 2 subsatellite paths near the time of SAR arc observations on September 29, 1967. The arc position is shown as observed from Fritz Peak (F) at 0905 UT. An Alouette 2 pass at ~0900 UT is indicated. Map adapted from *Norton and Findlay* [1969].

latitude. Near the left end of the panels, within the plasmasphere, there is relatively steady whistler activity, which terminates near 50° invariant latitude and is followed by intense complex VLF noise. In several intervals the VLF noise exhibits a relatively well-defined lower-cutoff frequency. An arrow or a pair of arrows indicates the approximate position at which the rate of whistlers propagating from the conjugate hemisphere drops to zero. This rapid decrease in whistler rate is interpreted as indicating the plasmapause with an uncertainty of about ±1°. An asterisk above the top record shows the invariant latitude of the steep low-latitude edge of the midlatitude trough as detected from the topside sounder experiment on Alouette 2 at 0908 UT (see Figure 1). The estimated 'position' of the arc at the time of the 1149 Ogo pass is shown by a horizontal bar between the first and second panels of Figure 2. This position was adopted from the report of *Norton and Findlay* [1969] and from information on movements of the arc provided by *Hoch et al.* [1968]. A slow poleward drift observed prior to the last presunrise appearance of the arc at 1125 UT was assumed to continue from 1125 to 1149 UT.

The VLF data show repeatability from orbit to orbit in terms of the broad features of the transition from whistlers to complex VLF noise effects. This repeatability, plus the close agreement between the VLF data and the Alouette trough measurements, indicates that a well-developed plasmapause was present and that it was coincident with the arc position to an uncertainty of about 1° in invariant latitude.

November 1, 1968, measurements. The upper and middle panels of Figure 3 show Ogo 4 plasmapause crossing data for the period from 1200 UT on October 30, 1968, to 1200 UT on November 1, 1968. The bottom panel includes the *Kp* index and horizontal bars indicating the times of observation of SAR arcs in the meridian plane of Ann Arbor, Michigan [*Roble et al.*, 1970]. The various symbols for Ogo 4 data represent real-time telemetry at Winkfield, England (WNK), Rosman, North Carolina (ROS), Fairbanks, Alaska (SKA), Byrd, Antarctica (BY), and Ororal, Australia (ACT). Dashed lines connecting pairs of symbols indicate the *L* range within which the plasmapause is estimated to lie. A single symbol indicates the estimated plasmapause position to be in the direction of the arrow and within $\Delta L \sim 0.3$. Ogo 4 was in the $\sim$ 0900–2100 LT plane, and separate plots of the data for $\sim$ 0900 MLT (upper panel) and $\sim$ 2100 MLT (lower panel) indicate substantial premidnight to post-dawn differences in plasmasphere radius. The asymmetry becomes relatively pronounced following the increase in substorm activity early on October 31. (The scale of plasmapause L value is linear in $1/L^2$ as a convenience

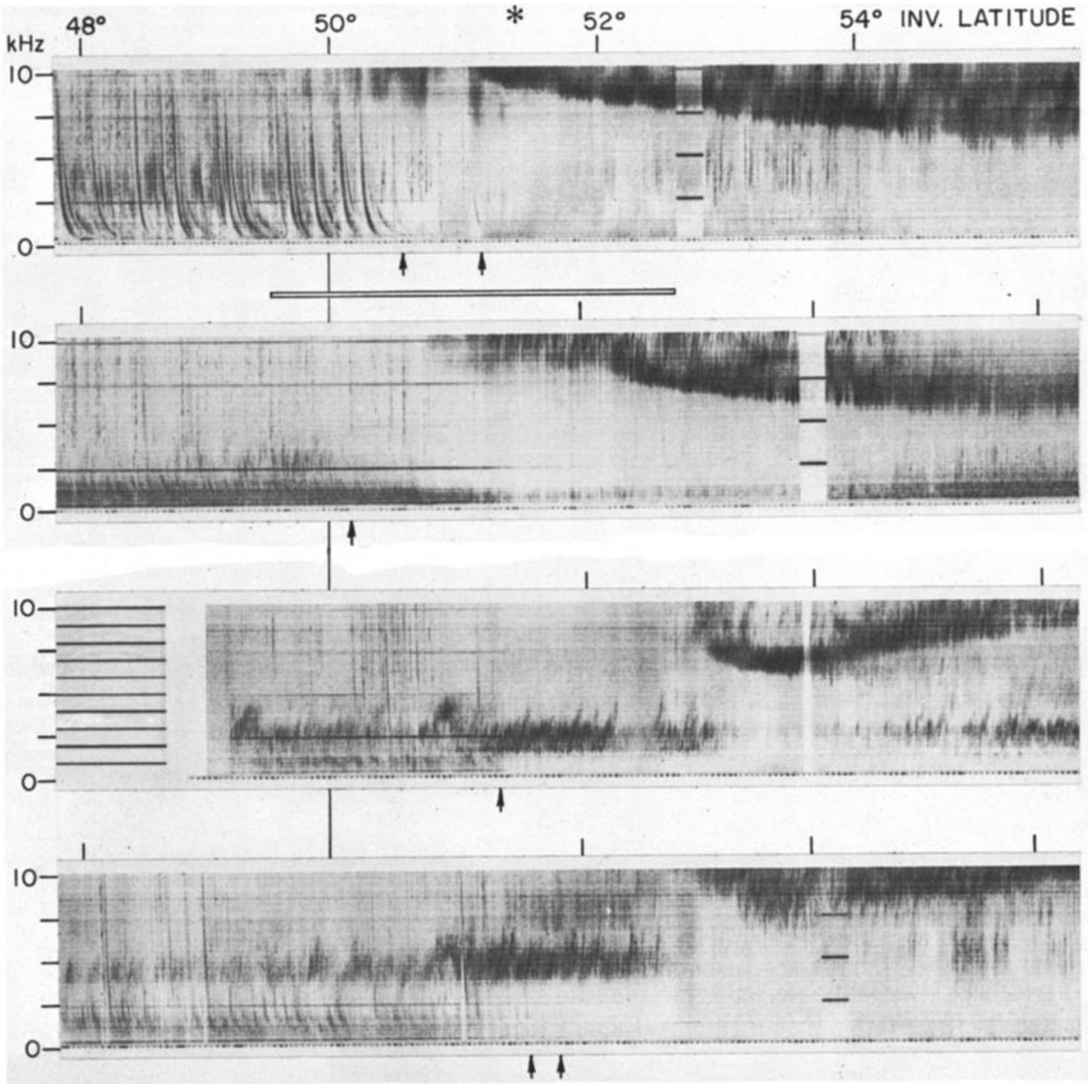

Fig. 2. Ogo 2 VLF spectra showing plasmapause crossings on the three passes indicated in Figure 1 and on a subsequent pass over Alaska. Frequency 0–10 kHz is displayed versus invariant latitude; the records are aligned vertically with respect to the time of crossing 50° invariant latitude (thin vertical line). An asterisk above the top record identifies the midlatitude trough as detected from Alouette 2 at 0908 UT (see Figure 1). A horizontal bar between the first and second panels shows the estimated 'position' of the arc at the time of the 1149 UT Ogo 2 pass (see text for details). First record, Rosman, North Carolina, 1004 UT, $\Phi = 0°$, 1158 km, 0518 MLT; second record, Rosman, North Carolina, 1149 UT, $\Phi = 327°$, 1153 km, 0400 MLT; third record, Fairbanks, Alaska, 1334 UT, $\Phi = 295°$, 1102 km, 0412 MLT; fourth record, Fairbanks, Alaska, 1520 UT, $\Phi = 268°$, 1046 km, 0416 MLT (values referred to 50° invariant latitude).

in representing $\mathbf{E} \times \mathbf{B}$ convection effects. In such coordinates the slope of a line is proportional to the east-west component of magnetospheric equatorial $\mathbf{E}$ by a factor that is independent of L.)

Details of the November 1 SAR arc comparison are shown in Figure 4, where L is plotted on a linear scale versus universal time (top) and magnetic local time (bottom). Open circles show the position of maximum arc luminosity as a function of time in the early hours of November 1, 1968, as observed from Ann Arbor (42°17′N, 83°45′W). As magnetic local time (bottom scale) varied from near 1900 to 0500 hours, the arc as observed in a north-south plane first moved steadily equatorward, then remained fixed for several hours, and later moved equatorward again. Arrows along the upper, UT scale show the times of the last 5 Ogo 4 passes plotted in Figure 3 for ~2100 MLT on October 31–November 1. These passes were on meridians crossing the Atlantic Ocean and eastern United States, the last pass being within a few degrees of the Ann Arbor meridian. The corresponding plasmapause crossing data are replotted in Figure 4 versus magnetic local time of crossing 50° invariant latitude. Near 2100 MLT the reported arc position is within $\Delta L \sim 0.1$ of the plasmapause position estimates from Ogo 4. The arc appears to be centered just equatorward of the plasmapause, but a strong statement on this point cannot be made on the basis of the present data.

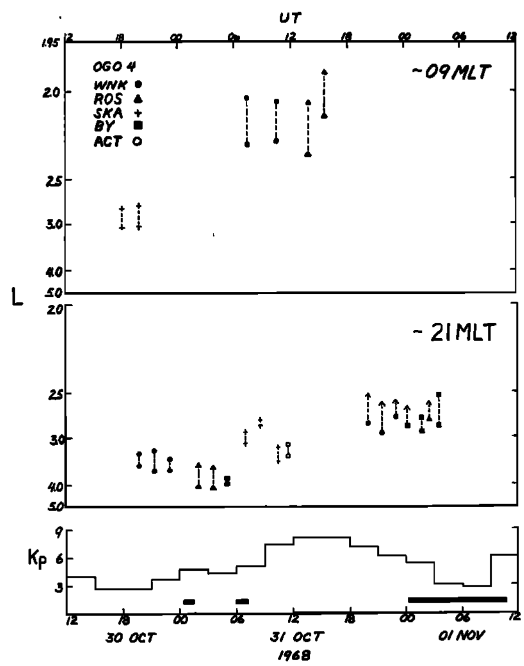

Fig. 3. Ogo 4 plasmapause crossing data for the period October 30 to November 1, 1968. Data from the ~0900 and ~2100 MLT sectors are shown separately to indicate the asymmetry of the plasmapause. Pairs of symbols indicate the L range (Jensen-Cain field) within which the plasmapause is estimated to lie. Single symbols indicate the plasmapause position to be in the direction of the arrow and within $\Delta L \sim 0.3$. Solid bars in the bottom panel indicate the times of observation of SAR arcs in the meridian plane at Ann Arbor, Michigan [*Roble et al.*, 1970]. See text for further details, including explanation of the L scale.

A tentative model of the arc-plasmapause relation in Figure 4 is as follows. Until about 0400 UT the plasmapause was relatively fixed in sun-earth coordinates, but it was tilted across the nightside toward lower L as suggested in Figure 3. The steadiness of the boundary is implied by the repeatability of the Ogo 4 data over the 2300–0400 UT period. The apparent motions of the arc as observed in a north-south plane are then due to motion of the station underneath a relatively rigid but asymmetric plasmapause. (Similar relationships have been inferred for other arc observations by *Glass et al.* [1970] and *Hoch and Smith* [1971].) At about 0400 UT on November 1 a period of relatively deep quieting began (see Kp in Figure 3). This quieting may have resulted in a decrease in the convection electric field, permitting the asymmetric plasmapause to approximately corotate with the earth [*Carpenter*, 1970] and causing the arc to appear at constant L. At about 0800 UT there was a renewed surge of substorm activity (see Kp in Figure 3) resulting in convective reconfiguration of the plasmapause and associated movement of the arc position. Near local dawn the arc approached $L \sim 2.1$. At the lower right Ogo 4 plasmapause crossing estimates from the 0900 MLT sector are shown, representing passes roughly 12 hours preceding and following the arc observations. There is good agreement, reinforcing the general impression of SAR arc activity along a highly asymmetric plasmapause.

October 31, 1968, measurements. As indicated in Figure 3, some limited observations of SAR arc activity were made from Ann Arbor on the night preceding the one just described

[*Roble et al.*, 1970]. The evidence again suggests a close relationship between SAR arcs and an asymmetric plasmapause. According to *Roble et al.* [1970], there was some indication of an arc-type enhancement near 0000 UT on October 31 at the approximate position in *L*-MLT space shown by the solid bar in Figure 5*a*. Data from four Ogo 4 plasmapause crossings in the 2100 MLT sector (see Figure 3) are plotted for comparison. Universal times of crossing 50° invariant latitude are indicated. There is relatively close agreement between the *L* values of the arc and the plasmapause, considering the separations of the measurements in universal time and in magnetic local time and certain difficulties in resolving the SAR arc features due to clouds.

Shortly after local midnight on October 31 an arc appeared near $L \sim 2.6$ and moved equatorward along the Ann Arbor meridian in the manner indicated by the solid bar in Figure 5*b*. The figure also shows Ogo 4 plasmapause crossings in the 2100 MLT and 0900 MLT sectors during several hours preceding and following this arc observation. The arc lies between the 2100 and 0900 MLT positions of the plasmapause and in particular appears to follow a 'tilted' line connecting measurements *G* and *H*, which were made at about the time of the arc observation. The spread in the 2100 MLT positions is probably related to a surge of substorm activity that began about 0700 UT on October 31 and resulted in substantial decreases in plasmapause radius (see Figure 3).

Concluding remarks. The Ogo 2 and Ogo 4 VLF data reported here indicate that the plasmapause and SAR arc agree in position within the $\sim\pm1°$ uncertainty in invariant latitude that is characteristic of the plasmapause measurements. This agreement corroborates the findings of *Chappell et al.* [1971], whose work was based on Ogo 5 thermal ion density data. The finding is also compatible with the reports of *Norton and Findlay* [1969] and *Norton and Marovich* [1969] on the proximity of a SAR arc to the midlatitude trough observed from Alouette topside soundings.

In the present work direct evidence has been shown of the existence during SAR arc observations of a plasmapause structure tilted across the nightside of the earth toward smaller *L* values. Some details of the arc motions as viewed from a ground station appear understandable in terms of such a structure fixed in sun-earth coordinates. Suggestions that this should be so have been made by *Glass et al.*

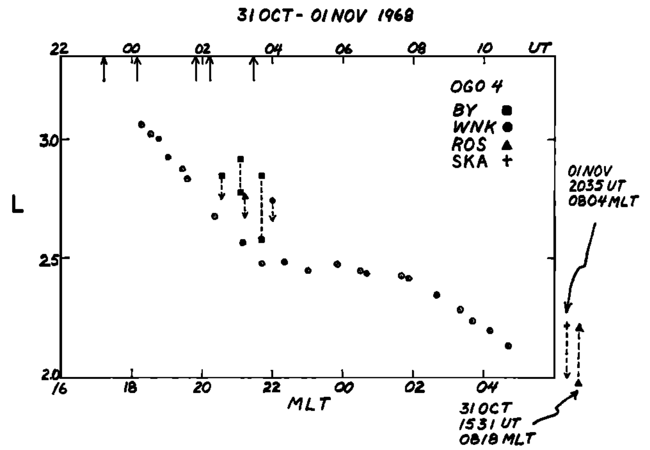

Fig. 4. Comparison of Ogo 4 plasmapause data and SAR arc position on November 1, 1968. *L* is plotted versus universal time (*top*) and magnetic local time (*bottom*). Open circles show the position of maximum arc luminosity versus time as observed in a north-south plane from Ann Arbor, Michigan [*Roble et al.*, 1970]. Arrows along the upper scale show the universal times of the last five Ogo 4 passes indicated in Figure 3, middle panel. The corresponding plasmapause information (filled symbols) is presented versus magnetic local time for comparison with the arc data. Additional Ogo 4 data from the dawn sector are at lower right. See text for details.

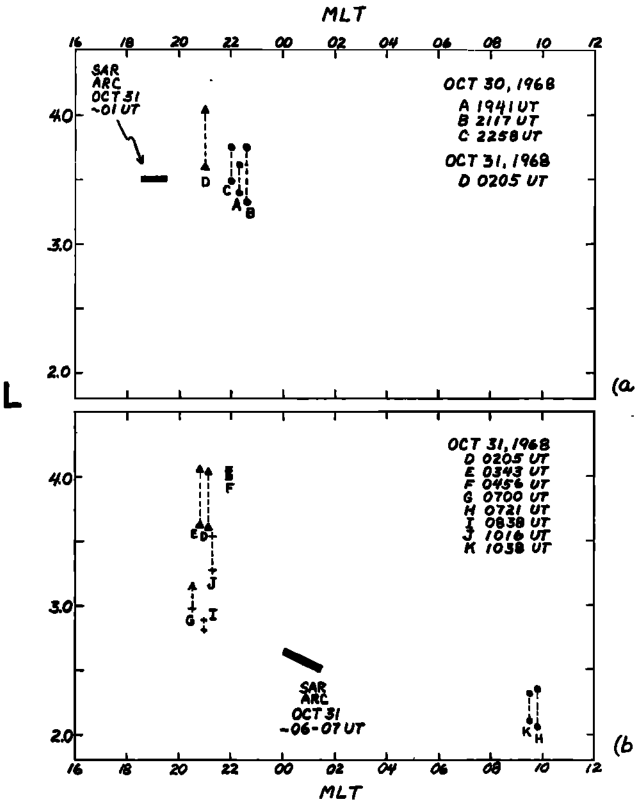

Fig. 5. Comparison of Ogo 4 plasmapause data and SAR arc positions on October 30–31, 1968. L is plotted versus magnetic local time. Universal time for the satellite data is listed. Solid bars show the approximate positions of SAR arcs observed from Ann Arbor, Michigan [*Roble et al.,* 1970]. The arc at ~0100 UT was not completely resolved owing to clouds in the observation area.

[1970] and *Hoch and Smith* [1971], among others. Certain other arc motions appear to involve reconfiguration of the plasmasphere during substorm-related convection events.

New observations are needed to clarify the detailed relationships of the arc, the plasmapause, and the associated electron-density trough in the ionosphere. It is possible that SAR arcs may be used as tracers of certain classes of convection phenomena.

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