Plasma Waves in the Dayside Polar Cusp
2. Magnetopause and Polar Magnetosheath

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During the outbound pass of November 1, 1968, Ogo 5 sporadically encountered the low-altitude polar cusp at low magnetic latitudes. The spacecraft remained in the cusp beyond \( r \approx 6 \, R_E \), and it then traversed the interface region between the magnetospheric cusp and the magnetosheath. Two large scale discontinuities were detected in this sheath-cusp transition region, and several possible interpretations are evaluated here. We show that at 1427 UT the local changes in magnetic field orientation and the variation in ULF magnetic power spectral density were typical of shifts detected at the magnetopause, although the spacecraft did not traverse a true boundary of warm plasma at this point. The second discontinuity, detected at 1456 UT, resembled a collisionless shock, and it was characterized by observations of intense, impulsive VLF electric field bursts and rapid local variations in both total ion flux and differential electron flux. However, beyond 1456 UT the spacecraft was still well within the magnetosheath, and the simplest interpretation is that Ogo 5 had traversed a standing shock within the sheath.

In recent years space scientists have been able to confirm directly that the earth’s magnetosphere is open. It is now known that some form of the solar wind plasma actually extends all the way to the ionosphere at high magnetic latitudes on the day side of the earth [Heikkila and Winningham, 1971; Frank, 1971; Russell et al., 1971]. This dayside polar cusp or cleft connects to the auroral oval, and various wave-particle interaction processes that occur in the cusp region can affect the properties of the auroral particles and contribute to scattering of particles onto closed magnetospheric field lines. Recent studies of Ogo 5 data, from a period on November 1, 1968, when the spacecraft entered the cusp during a large magnetic storm, showed that field-aligned currents drive certain plasma instabilities on the cusp boundaries at low altitudes [Scarf et al., 1972; Fredricks et al., 1973], and that Kelvin-Helmholtz or drift instabilities can produce other observed wave modes [D’Angelo, 1973; Fredricks and Russell, 1973]. The associated wave-particle scattering appears to be sufficiently strong to provide enhanced electrical resistivity so that parallel electric fields develop, and these parallel fields may account for some auroral acceleration phenomena.

Although the open versus closed magnetosphere configuration controversy is now resolved, and some understanding of the dynamical processes occurring in the low-altitude cusp has been obtained, many fundamental questions concerning the structure and properties of the dayside cusp are still unanswered. One important area of uncertainty involves the phenomena that develop in the magnetosheath-polar cusp interface region. It was recognized long ago [e.g., Dungey, 1958] that the conventional conditions used to define the local orientation of the magnetopause give singular results at the neutral points, and this fact requires the existence of an indentation in the boundary near each neutral point. Walters [1966] noted that the boundary indentation occurs in a region of supersonic magnetosheath flow, and he suggested that this would result in the formation of a neutral point shock wave attached to the magnetopause. However, Spreiter and Summers [1967] argued that attached shocks of this type would not develop because the magnetosphere is not a solid obstacle to the flow. These authors developed a very different model for fluid flow around the high-latitude magnetosphere by allowing the obstacle to adjust its boundary shape. They introduced the concept of a smooth streamline of constant pressure across the neutral point indentation to separate the supersonic magnetosheath flow from a hot stationary or stagnant plasma trapped in the cusp-shaped region in the vicinity of the indentation.

The fluid models form a useful general framework for discussion of the dayside neutral points, but it has frequently been proposed that much more complex physical phenomena occur in this region. Dungey [1961, 1963] suggested that the interplanetary magnetic field merges with the geomagnetic field at the dayside magnetopause, and this concept was extended and generalized by Levy et al. [1964], Azford et al. [1965], and others. In such models the polar cusp contains magnetic field lines that have recently merged with interplanetary field lines, and since wave-particle interactions can provide a dissipation mechanism, it can be anticipated that enhanced wave levels will be detected near the neutral points. In this connection, it
is worth noting that a standing magnetosheath shock might develop at high latitudes even if there is no magnetospheric bulge. Dryer [1967] proposed that an attached shock associated with wave coalescence could form under certain circumstances.

There have been few extensive studies of plasma, wave, and field phenomena in the region of the neutral points. The Heos 2 experimenters [Paschmann et al., 1973] recently reported on the existence of the so-called ‘polar mantle’ just within the magnetopause over the polar caps. This region contains a reduced flux of plasma with a characteristic magnetosheath velocity distribution, and apparently the mantle formation provides a means for removal of the magnetopause bulge. However, many questions remain about the stability of the cusp–sheath interface, the characteristics of the low latitude boundary of the cusp, and the variability of this region when unsteady solar wind conditions are encountered.

On November 1, 1968, the Ogo 5 spacecraft penetrated the dayside cusp at low altitudes and traversed the magnetosheath–polar cusp interface region. In this report we discuss the Ogo 5 plasma wave and magnetic field observations in the expected region of the neutral point. The magnetopause is tentatively defined in terms of changes in the low-frequency magnetic fluctuation levels, and it is shown that a strong discontinuity, marked by a distinct enhancement and variation in the high-frequency plasma turbulence spectrum, was encountered beyond this magnetopause. The analysis of the Ogo 5 field and wave measurements is supplemented by comparison with simultaneous interplanetary magnetic field orientation data from Explorer 33. If we assume that the November 1, 1968, observations are typical of neutral point phenomena, rather than being associated with the large magnetic storm, we can conclude that collective plasma physics processes do play an important role in this region of the magnetosheath.

**General Description of the Ogo 5 Measurements**

On November 1, 1968, the Ogo 5 satellite was outbound through the dayside magnetosphere, and the trajectory remained close to the 45° magnetic latitude projection out to about 10-11 Re. At 1220 UT, when the spacecraft altitude was 2.2 Re, the solar wind plasma probe first detected large fluxes of warm electrons with characteristic magnetosheath energies \( N_e \approx 10 \text{ cm}^{-3}, \ kT_e \approx 200 \text{ eV} \), and Russell et al. [1971] interpreted these observations in terms of the initial Ogo 5 encounter with the dayside polar cusp plasma. There were several additional isolated cusp encounters between 1250 and 1330 UT, and after about 1345 UT (spacecraft altitude equal to 6 Re), electrons with \( kT_e \geq 300 \text{ eV} \) were continuously detected. The central panel in Figure 1 summarizes these electron measurements in terms of an energy density versus time plot. The top and bottom panels of this figure contain general information on the changes in VLF electric field wave amplitudes (for each 3.23-min interval, the maximum and minimum values of the wideband 1- to 22-kHz levels are plotted), and the ULF magnetic fluctuation variations \( B_{rms} \) is the standard deviation for a 1-min accumulation of magnetometer data.

Several very detailed studies of the low-altitude cusp properties on November 1, 1968, have already been completed. Scarf et al. [1972] presented a general survey of the ULF and VLF activity out to 1500 UT \( (r \approx 9 \text{ Re}) \), along with an intensive analysis of the cusp boundary observations before 1345 UT. Fredricks et al. [1973] and Fredricks and Russell [1973] carried out more detailed studies of these low-altitude measurements, and the authors showed that for \( r \leq 6 \text{ Re} \) the most intense wave activity developed in small subregions where strong field-aligned currents flowed. Kivelson et al. [1973] analysed the motion and changes in structure of the cusp in terms of response to variations in interplanetary or magnetosheath field orientation; the phenomena observed in the interval between 1345 and 1430 UT are briefly discussed by Kivelson et al., but once again the emphasis in their study was on the measurements made before 1345 UT, when Ogo 5 was well below the magnetosheath.

Here we focus attention on the Ogo 5 measurements made after 1420 UT, when the spacecraft was emerging from the dayside polar cusp into the magnetosheath proper. The lower part of Figure 2 shows the Ogo 5 trajectory (radius versus magnetic latitude) for the interval 1145–1500 UT on November 1, 1968, and the spacecraft location for the period of special interest (1420–1500 UT) is marked by a heavy line segment. The light curve marked ‘first polar cusp encounter’ and the corresponding one that intersects the trajectory at 1315 UT are taken from Figure 13 of Russell et al. [1971]. The short arrows show the measured magnetic field orientations in these coordinates between 1220 and 1315 UT, and the cusp boundary curves are drawn by requiring the field to be parallel to the observed field near Ogo 5, and dipolar near the earth. Above the Ogo 5

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**Fig. 1.** Some characteristics of the Ogo 5 field, particle, and wave measurements during the outbound pass of November 1, 1968. The spacecraft was intermittently within the polar cusp at low altitudes (before 1325 UT), and the cusp-magnetosheath transition was traversed between 1420 and 1500 UT. The quantity \( B_{rms} \) is the standard deviation associated with 1-min averages of the field magnitude.
trajectory curve we sketch a possible form for the polar cap boundary of the cusp, to show the general field orientation expected in this region. At the top of Figure 2 we show the measured field orientations, as given by 1-min averages of field readings projected onto a plane containing the sun-earth line and the dipole north direction.

The magnetic field data shown in Figures 1 and 2 suggest that Ogo 5 was within the magnetospheric cusp before about 1427 UT. The rms fluctuation levels were low before this time, and the field orientation was steady and parallel to the nominal cusp boundary direction. The $B$ field observations also indicate that the spacecraft was within the magnetosheath after about 1455 to 1500 UT; the rms fluctuation levels in this outer region were high and variable (Figure 1); and the 1-min averages of the magnetic field direction (Figure 2) were consistent with results expected for a field embedded in shocked solar wind flowing parallel to the nominal magnetopause. However, the data of Figures 1 and 2 also reveal that some complex changes occurred within the transition region between the magnetospheric cusp and the magnetosheath. From Figure 1 it can be seen that the wideband electric field noise began to increase in a very gradual way near 1427 UT, but that large-amplitude bursts were observed near 1448-1451 UT and again just before 1500 UT. Figure 2 also shows that there were several shifts in the average $B$ field orientation between 1420 UT, when the field was aligned with the cusp, and 1500 UT, when the magnetosheath-type orientation was measured.

In terms of the local averages and amplitude ranges shown in Figures 1 and 2, the transition region observations might be interpreted in a number of distinct ways. For instance, it could be conjectured that Ogo 5 entered the magnetosheath at 1427 and that the spacecraft encountered the attached shock at 1456 UT, when the highly variable electric field bursts were detected. Alternatively, it could be concluded that Ogo 5 entered the 'stagnant region' at 1427 UT and passed into the free-stream magnetosheath at 1456 UT. On the other hand, Figure 2 shows that the average $B$ field measured between 1430 and 1448 UT was oriented more or less parallel to the hypothetical northern boundary of the polar cusp, and one might speculate that Ogo 5 intermittently went into the polar cap magnetosphere until 1456 UT. Finally, it is necessary to consider the possibility that some variations during this interval were associated with changes in solar wind parameters.

Clearly, the determination of the validity of any of these interpretations requires examination of all available local data with much higher time resolution and the use of independent observations from other spacecraft. This analysis is taken up in the next section.

**Analysis of the Cusp–Sheath Interface**

Between 1325 and 1500 UT on November 1, Ogo 5 was transmitting only digital data at the 1-kbit/sec telemetry rate, and the vector magnetic field was measured once every 1.15 sec. The highest-resolution plasma wave information (also one sample per 1.15 sec) came from the slowly-scanning spectrum analyzer connected to the short electric dipole antennas. The frequency scan covered the range 0.56 to 70 kHz in seven narrowband channels with the analyzer remaining at a fixed frequency for 27.6 sec and the entire spectral scan being repeated every 3.23 min.

The top three panels of Figure 3 show some of the high-resolution field and wave measurements from Ogo 5 for the 1420- to 1500-UT interval. Every measured point is shown for the electric field wave amplitudes, but some smoothing has been put into the magnetic field plots, and averages over a few seconds are displayed here. The single component labeled $B_e$ represents the observations from the fluxgate oriented along the spacecraft X axis; at this time the Ogo X axis direction cosines in geocentric solar magnetospheric (GSM) coordinates were $(0, -0.819, 0.575)$.

At 1500 UT on November 1, 1968, the Explorer 33 spacecraft was in the solar wind, and the location in geocentric solar ecliptic coordinates was $X = 34.25 R_e$, $Y = -23.2 R_e$, $Z = -14.5 R_e$. We are grateful to Dr. D. Colburn for supplying us with the high resolution (approximately one sample per 6 sec) Explorer 33 field data in GSM coordinates. It should be noted that the Explorer 33 measurements have been plotted with a time delay (relative to Ogo) of approximately 6.3 min, to account for the travel time between Explorer and Ogo. Recently Kivelson et al. [1973] compared the onset times for the low-altitude cusp encounters with north-south changes in Explorer 33 magnetic field orientation, and they found a good correspondence for a total time delay of 8 min. This value was shown to be consistent with expectations based on the known locations of the two spacecraft for the unusually high magnetosheath flow speed conditions (up to 1000 km/sec) measured on Vela 4B before 1415 UT [Russell et al., 1971]. However, for the specific time interval of interest here (i.e., after 1427 UT), no magnetosheath or interplanetary plasma velocity measurements are available, and

![Figure 2](image-url)
we simply choose a somewhat smaller time delay that appears to provide the best correlation between changes in $B_z$ (Explorer) and $B_y$ (Ogo).

Before 1426–1427 UT, it is clear from Figure 3 that Ogo 5 was not in the magnetosheath because the field magnitude and direction were very stable. The onset of magnetic noise and the change in field direction near 1427 UT may be characterized in terms of a conventional magnetopause crossing, and the crossing appears to be correlated with onset of a southward component for the interplanetary field. The other large changes in $B_z$ at 1440 and 1448 UT also appear to be well correlated with interplanetary $B_z$ variations detected on Explorer at about 1436 and 1441 UT. Finally, a less dramatic change in the Ogo $B$ field data (the decrease in $|B|$ detected at 1456 UT) appears to be well correlated with the second onset of a fairly steady southward interplanetary field, encountered on Explorer at 1450 UT.

If one focuses attention only on the Ogo and Explorer magnetic field plots of Figure 3, very limited conclusions can be drawn. It is clear that Ogo 5 was within the cusp before 1426 UT, and it appears very likely that the spacecraft was in the high-latitude magnetosheath after 1456 UT, because thereafter the measured field magnitude was significantly smaller. From the data shown here it also appears conceivable that Ogo skirted the cusp briefly between 1440 and 1442, and again between 14h 52m 30s and 1454 UT; the values of $|B|$ and $B_z$ during these periods were similar to the values measured before 1426 UT. However, from examination of the magnetic field profiles alone, it is not possible to establish much more than this with any certainty. Clearly the phenomena detected at the position of Ogo 5 varied in accordance with changing interplanetary magnetic field characteristics, but this would be a likely occurrence for any of the models described at the end of the last section.

Additional information of significance comes from examination of the $E$ field spectral scans. The top panel in Figure 3 confirms the general conclusion from Figure 1 that the abrupt change in ULF magnetic noise detected at 1427 UT was not associated with a discontinuous enhancement in the VLF electric field noise levels. Instead, the 1427 crossing marked the beginning of a period of continuous but gradual elevation for virtually all the VLF $E$ field channel amplitudes, with additional intense and sporadic enhancements being detected only in the 500-Hz electric channel. However, even at this lowest frequency, there was a distinct difference between the $E$ and $B$ responses. The top two panels in Figure 5 of Scarf et al. [1972] summarize the simultaneous $E$ and $B$ measurements made in identical 500-Hz, 15% bandwidth channels for this period, and it can be verified that at $f = 500$ Hz, the $B$ field amplitudes jumped abruptly to tens of milligauss at 1427 UT, while the $E$ field levels merely started to rise gradually.

The top panel of Figure 3 shows an additional important point. The discontinuity at 1456 UT was associated with a very unusual large-scale change in the VLF electric field spectrum. Although the presence of a very brief data gap that occurred near 14h 56m 40s UT tends to obscure the timing of this change, as is shown in Figure 3, careful inspection of the $E$ field data shows that sporadic and very intense electric field bursts were detected in all VLF channels after about 14h 56m 20s UT. It is this discontinuity that we tentatively interpret in terms of traversal of the attached shock, or traversal of the boundary between the stagnant plasma and the free stream.

![Fig. 3](image.png)

Fig. 3. A plot of some Ogo 5 field and plasma wave observations, together with $B_z$ (GSM) from Explorer 33. Explorer was located in the solar wind, and the time scales have been shifted by 6.3 min to account for the interplanetary and magnetosheath travel time. The changes in Ogo 5 magnetic field characteristics at 1427 UT resemble those usually found at the magnetopause. The large-scale change in VLF electric field characteristics near 1456 UT indicates that Ogo 5 encountered another shocklike discontinuity at this point.
It is clearly of importance to determine whether or not Ogo 5 was in the magnetosheath before 1456 UT, and we first turn to an Ogo-Explorer B field comparison in geocentric solar magnetospheric (GSM) coordinates that is more meaningful in this regard than the simple plots shown in Figure 3. In this reference frame, some striking relations become obvious. For instance, between 1428 and 1456 UT, the two sets of measured \( z \) components are very highly correlated, with \( B_z \) (GSM, Ogo, \( t \)) approximately equal to \( 4B_z \) (GSM, Explorer, \( t - 6.3 \) min), to within about 20%. On the average, the \( B_z \) components satisfy a similar relation, but throughout the period, large-amplitude oscillations in the \( y \) components were measured on both spacecraft, and these time-lagged \( y \) components were not as well correlated as the \( z \) components were (an indication of the large excursions in \( B \) (GSM) measured on Ogo 5 for this interval is given by Russell et al. [1971, Figure 10]). However, in terms of the \( B_z \) (GSM) profiles, a simple comparison of shifted component values versus time does not reveal any simple correlation, because there are several intervals where \( B_z \) (Ogo, \( t \)) and \( B_z \) (Explorer, \( t - 6.3 \) min) have different signs. Therefore, we turn to an alternate representation of the measurements. The top part of Figure 4 is identical to the top of Figure 2, and on the bottom of Figure 4 we plot corresponding averages of Explorer 33 field data projected into the same plane. This form of data presentation also suggests strongly that after 1427 UT the magnetic fields measured on Ogo were very closely related to the interplanetary fields measured 6.3 min earlier on Explorer. The Ogo distributions can be classified into a few segments with fairly well-defined orientations. For instance, in the intervals 1430 to 1440 UT, 1442 to 1446 UT, and 1448 to 1500 UT (with the exception of the time period around the 1450-UT discontinuity) the field direction measured at Ogo remained relatively steady. It can be seen from the bottom panel in Figure 4 that steady \( B \) field orientations were also detected during the corresponding intervals on Explorer 33, and this already suggests that Ogo was in the magnetosheath after 1427 UT.

If Ogo was indeed in the sheath and near the magnetopause during this interval, the observed shifts in mean field orientation (relative to Explorer) can be explained in terms of 'refraction' associated with shocked solar wind flow at high latitudes. At 1500 UT, Ogo 5 was high above the equator (solar ecliptic coordinates: \( X = 3.6R_s, Y = 1.8R_s, Z = 7.0R_s \)) but the local magnetosheath plasma would generally be on a streamline starting nearly from the subsolar bow shock (\( Z \ll 1R_s \)), since only the subsolar streamline actually contacts the magnetopause in fluid models with Chapman-Ferraro boundary conditions. Thus the sheath flow velocity vector changes needed to get the plasma up to very high latitudes would also refract the imbedded magnetic field; this type of explanation can account for the mean Ogo orientation measurements in terms of shocked solar wind flow toward the northern polar cap, and (with the exception of the brief shift near 1456 UT) it does appear that the field measurements after 1427 UT are compatible with the assumption that Ogo 5 was in the conventional magnetosheath, rather than in a stagnant region, or polar cap magnetosphere.

A more definitive test of this conclusion comes from analysis of the microstructure of the observed ULF fluctuations, because the magnetic power spectral densities measured in specific regions of the earth's magnetosphere and magnetosheath do have characteristic forms. Since November 1, 1968, was a day of intense magnetic storm activity, it is useful to consider first some quiet control days for which Ogo 5 was in nearly the same spatial regions to determine the characteristic high-latitude magnetosheath and magnetosphere fluctuation spectra. Scarf et al. [1972] used the outbound passes of October 27, 1968, and November 6, 1968, as the comparison days for November 1 because the trajectories were comparable, although Ogo 5 did not encounter the dayside cusp on these quiet days.

On November 6 and October 27, 1968, the spacecraft telemetry rate was 8 kbits/sec, and the Nyquist frequency was 3.47 Hz. Figure 5 contrasts a typical high-latitude magnetospheric spectrum (from October 27) with high-latitude spectra.
magnetosheath spectra computed for both control days, and it can be seen that the magnetosphere and magnetosheath spectra have very different frequency dependences. In the magnetosphere the spectrum falloff is very steep for \( f > 10^6 \) Hz, and, in fact, this October 27 magnetospheric power spectrum is very similar to the spectrum computed from November 1, 1968, data for a period (before 1456 UT) when Ogo 5 was outside of the polar cusp at low altitudes [Russell et al., 1971, Figure 12]. The magnetosheath spectra for October 27 and November 6 fall off much more slowly with increasing frequency, and in the range \( 10^4 \leq f \leq 0.5 \) Hz, the two curves are virtually identical to one another but differ very much from the typical magnetospheric spectrum.

Figure 5 also shows the power spectrum for the period 1427–1447 UT, on November 1, when the Nyquist frequency was 0.43 Hz. It can be seen that before 1456 UT the wave power was 2 orders of magnitude higher on November 1 than on the control days, but the slope of this November 1 curve is virtually identical to the slope for the corresponding normal magnetospheric power curves of October 27 and November 6 for \( f \leq 0.5 \) Hz. This similarity also indicates that Ogo was within the magnetosheath after 1427 UT.

At 1500 UT on November 1 the spacecraft telemetry rate was changed to 8 kbits/sec, so that the magnetometer Nyquist frequency became 3.47 Hz. The corresponding power spectral density for the beginning of this interval (1501–1521 UT) is shown in Figure 5, and it can be seen that the spectral shape differed from the others in that it exhibited a broad peak with a nearly flat slope extending out to about 0.1 Hz. However, for \( f \geq 0.1 \) Hz, this post-1456 UT power spectrum also dropped off with increasing frequency; thus, although the wave power was shifted to higher than normal frequencies in the spacecraft frame of reference, the high-frequency slope of the spectrum in this region again appeared to be characteristic of the normal magnetosheath variation. The most reasonable explanation for this shift in power spectral density near 1500 UT is that Ogo encountered a magnetosheath discontinuity associated with a rise in velocity at 1456 UT. The shift in wave power to higher frequencies after 1456 and the appearance of a flat peak below about 0.1 Hz can then be explained in terms of Doppler shifting of the more normal magnetosheath magnetic fluctuation spectrum. Similar broadened spectral density functions have also been observed in the postshock magnetosheath [Olson and Holzer, 1973].

On the basis of analyzing the changes in characteristics of the ULF magnetic spectral densities, we conclude that Ogo 5 did enter the magnetosheath at 1427 UT and that the spacecraft then entered a region with much higher sheath flow velocities at 1456 UT. During this entire period the two JPL plasma probes on Ogo 5 were in operation, and the plasma observations are generally consistent with the above conclusions. However, the particle measurements do not contribute unambiguous information on the nature of these boundaries because of the slow sampling in use before 1500 UT and the large inclination of the local ion flow direction to the solar direction.

The JPL plasma probe that points radially away from earth was in the electron mode on November 1, and it measured the energy spectrum of electrons in the range 50 eV to 3200 eV once every 295 sec. As is shown in Figure 1, at about 1427 UT the observed electron energy density did start to climb above the representative polar cusp values with a steep and fairly steady profile (see also the discussion by Russell et al. [1971]). The streaming speed cannot be determined from the electron data, and these observations cannot distinguish between cusp and sheath. Nevertheless, the boundary at 1427 was marked by an abrupt change in the electron energy spectrum, as well as by the gradual variation in average energy already shown in Figure 1. Before 1425 UT the measured spectrum had a broad and fairly stable tail with differential current at 800 eV approximately 20 to 30% of the value at 400 eV, but between 1427 and 1435 UT the spectrum dropped much more steeply with increasing energy, and the same flux ratio was near 5%.

The solar-oriented plasma probe was in the ion mode, but before 1500 UT only the Faraday cup measurement of total ion flux (\( E/Q \) range: 100 to 11,000 V) was above background. This cup does have a fairly wide acceptance cone of \( \pm 20.3^\circ \) [Neugebauer, 1970], but it was pointed at the sun, and the measured flux is therefore only a lower limit for anticipated high-latitude magnetosheath flow conditions. Throughout the November 1, 1968, outbound pass, the solar-oriented Faraday cup generally detected some positive ions whenever the other plasma probe measured cusp or sheath electrons, but the ion fluxes were low in most regions and highly variable. Near 1345 UT, the positive ion flux went from background to about \( 4\times10^5 \)
cm$^{-2}$ sec$^{-1}$, and the average remained near this level with a few excursions up to $7 \times 10^9$ cm$^{-2}$ sec$^{-1}$. Between 14h 26m 20s and 14h 27m 10s, the measured ion flux only varied between 5.0 and $6.5 \times 10^9$ cm$^{-2}$ sec$^{-1}$, and it then jumped to about $1.5 \times 10^{10}$ cm$^{-2}$ sec$^{-1}$ (at 14h 27m 20s UT). Large variations in measured ion current (presumably associated with changes in the direction of plasma flow persisted after this time, but between 1431 and 1500 UT all measurements gave $j_i > 1.8 \times 10^9$ cm$^{-2}$ sec$^{-1}$. This systematic shift in the measured ion current is quite consistent with the interpretation that Ogo was in the sheath after about 1427 UT.

All the relevant diagnostic instruments detected very significant changes in parameters at 1456 UT. As was noted in the discussion of Figure 3, extremely intense and variable broadband electric field noise developed after 14h 56m 20s UT, and the mean field magnitude dropped at this point, suggesting that Ogo had traversed some sort of collisionless shock, emerging into the upstream region. The power spectral density shown in Figure 5 for the interval 1501 to 1521 UT is also consistent with the interpretation that Ogo had traversed a shocklike discontinuity into a region with higher plasma flow speed. In fact, there is direct evidence that the sheath velocity was extremely high shortly after this time. Between 1500 UT and 1508 UT, the solar-oriented curved plate analyzer detected streaming protons in several differential E/Q channels. It was apparent that the analyzer was measuring characteristics of the wings of the distribution function before 1508 UT (when the streaming direction changed), but enough information was available to conclude that the streaming speed was near 1000 km/see during this 8-min interval.

It is of interest to examine the discontinuity at 1456 UT in more detail. The bottom panels of Figure 6 again show the VLF E field and de B field observations for the last 10-min interval of 1-kbit/sec sampling, and the top two panels show the measurements made by the two JPL plasma probes in the correct time sequence. It is clear that before 1455 UT the electron distribution was well defined, and the positive ion flux was reasonably steady. It is also evident from the presentation of Figure 6 that the local particle distributions were very different after 1456. The peak ion flux values were significantly higher, and the variability was greater than before encounter with the discontinuity. The last differential electron spectrum shown here also exhibits variability for energies below about 800 eV, and it is clear that temporal variations on time scales of several seconds or less produced significant aliasing. The irregular nature of the electron and plasma wave spectra and the detection of large fluctuations in $j_i$ suggest that Ogo 5 may actually have remained within this discontinuity for several minutes. However, the variability of the ion flux after 1456 UT is probably representative of the fact that Ogo 5 was now within the magnetosheath rather than in quiet solar wind. When upstream waves are present, there are similar changes in flux levels across the bow shock, but on these occasions both upstream and downstream profiles of $j_i$ exhibit significant fluctuations.

The complete analysis of the Ogo 5 and Explorer 33 data for the time period after 1420 UT would appear to rule out some of the tentative interpretations discussed at the end of the preceding section. Since the ULF magnetic power spectral density for the 1427–1447 UT interval had a characteristic magnetosheath-type frequency variation, it is difficult to avoid the conclusion that the plasma was flowing with a representative sheath speed in this region. Accordingly, we consider it unlikely that Ogo reentered the magnetosphere here, or that it was passing through a stagnant plasma region. Since the brief and sudden shocklike change in B field orientation (see Figure 4) and magnitude (see Figure 6) detected at Ogo near 1456 UT corresponded only to a smooth and gradual change in interplanetary B field orientation (see Figures 3 and 4), we cannot attribute detection of the discontinuity on Ogo to passage of any corresponding interplanetary event. The one interpretation that appears easiest to reconcile with the entire body of observations is that Ogo passed from the polar cusp into doubly shocked solar wind at 1427 UT, and that it traversed an attached shock, emerging into the normal magnetosheath or singly shocked solar wind at about 1456 UT.

**FIELD AND WAVE OBSERVATIONS AFTER 1500 UT, NOVEMBER 1, 1968**

At 1500 UT the Ogo 5 telemetry rate was changed to 8 kbits/sec, and the special purpose or analog telemetry link was commanded on. Although the plasma conditions were considerably less turbulent at this time than they were a few minutes earlier, the availability of the higher-resolution

![Fig. 6. Details of Ogo 5 measurements near the 1456 UT discontinuity. The electron spectrum was measured using a curved plate analyzer pointed radially away from earth. The total ion current was measured using a Faraday cup pointed toward the sun. The ion flux readings plotted with dotted points were obtained in a mode with digitization accuracy of $\pm 1.5 \times 10^8$ cm$^{-2}$ sec$^{-1}$, and the ones without dots have $\pm 1.5 \times 10^9$ cm$^{-2}$ sec$^{-1}$ accuracy.](image-url)
Fig. 7. Variations in $|\mathbf{B}|$ and in the 560-Hz $E$ and $B$ wave amplitudes after 1500 UT, when the parameters were sampled once per 144 msec. At this time the plasma flow speed was near 1000 km/sec, and the changes measured in the spacecraft frame of reference may be aliased. Detailed analysis suggests that these 560-Hz $B$ field peaks represent high Fourier components of the ULF magnetosheath field fluctuations, while the 560-Hz $E$ field peaks are associated with development of electrostatic waves in the gradients of $|\mathbf{B}|$.

Data makes it worthwhile to provide a brief description of some measurements after 1500 UT.

Figure 7 shows one sequence of variations in the magnetic field strength and in the $E$ and $B$ wave amplitudes from identical 15% bandwidth channels centered at 560 Hz. Each parameter was sampled once per 144 msec, and all points are plotted in the figure. At first glance, it appears that the magnitude of the dc field was varying very rapidly over unusually wide ranges (for instance, just after 15h 04m 35s UT, the measured $|\mathbf{B}|$ apparently went from 50 to 148 $\gamma$ in 144 msec), and that intense $E$ and $B$ wave amplitudes at 560 Hz were generally correlated with each other and with the enhancements in $|\mathbf{B}|$. However, a more careful examination of the data shows that the observations in Figure 7 may actually be fairly representative of normal magnetosheath conditions.

Since the local flow speed was near 1000 km/sec here, the peak $B$ field rise time of 144 msec can be associated with a gradient scale length of about 70 km in the rest frame. Magnetic field variations with scale sizes as small as $\delta = c/\omega_p$ (the electron inertial length) have been reported at the earth's standing bow shock [Fredricks et al., 1968] and at current layers in the magnetosheath near the shock [Scarf et al., 1970]. However, since the electron density was of the order of 80 cm$^{-3}$ at 1500 UT [Russell et al., 1971], $\omega_p/2\pi$ was near 81 kHz, so that $\delta$ was approximately 0.6 km. Thus the observed scale length was actually much longer than the anticipated minimum value, assuming that there were no oscillations in $|\mathbf{B}|$ between the points plotted with separation of 0.144 sec. The 8-kbit/sec telemetry rate is obviously far too low to resolve gradients as small as 1 km for sheath flow speeds of 1000 km/sec, and we conclude that there is no reason to believe that this $|\mathbf{B}|$ profile is exceptional in any way.

There also appears to be a straightforward explanation for the 560-Hz $B$ field observations that are well correlated with $|\mathbf{B}|$. The peak noise levels of $10^{-1}$ $\gamma$ are measured in a channel with 84-Hz bandwidth, and the peak power spectral density is thus almost $1.2 \times 10^{-4} \gamma^2$/Hz. However, the 1501–1521 ULF magnetic power spectral density shown in Figure 5 may be extrapolated with constant slope (on the log-log plot) up to 560 Hz, and it can be seen that the predicted noise level in this VLF channel does just correspond to a spectral density near $10^{-4} \gamma^2$/Hz. In fact, close inspection shows that the 560-Hz $B$ field peaks are generally detected where $d|\mathbf{B}|/dt$ is largest, supporting the interpretation that in the spacecraft frame of reference the VLF channel was simply measuring high Fourier components of the dc field changes.

All the strong 560-Hz $E$ field enhancements (with the exception of the noise burst detected near 15h 04m 23s UT) also occurred when steep gradients of $|\mathbf{B}|$ were observed. Once again, careful inspection of the original data reveals that the 560-Hz $E$ peaks were generally displaced from the $B$ field maximums. Since current-driven plasma instabilities generate strong VLF electrostatic noise bursts in the gradients of $|\mathbf{B}|$ at the bow shock [Fredricks et al., 1968] and at other current layers in the magnetosheath [Scarf et al., 1970], a likely interpretation is that the 560-Hz $E$ and $B$ curves of Figure 7 represent observation of completely distinct phenomena. The VLF $B$ variations reflect changes in $|\mathbf{B}|$, while the $E$ enhancements correspond to current-driven plasma instabilities. In fact, some aspects of the measurements force one to discard any interpretation that the $E$-$B$ spikes are correlated components of an electromagnetic wave. For instance, the enhancements at 15h 04m 17s have an $E$ to $B$ ratio that would give an index of refraction less than unity for a hypothetical electromagnetic wave with frequency $f_{\text{LHR}} \ll f \ll f_{\text{cR}}$. Since the conventional dispersion relations preclude such a wave mode, we regard these $E$ field enhancements as electrostatic waves generated at the gradients of $|\mathbf{B}|$.

More information on the VLF electric fields can be obtained from the analog telemetry data, and Figure 8 shows the broadband $E$-field dynamic spectrum, the narrowband amplitude variation, and the profile of $|\mathbf{B}|$ for a later interval when the spectrum analyzer was measuring 3.0- and 7.35-kHz wave levels. The line drawings in Figure 8 again generally
show that the VLF E-field amplitudes rose in regions with steep gradients in $B$. The frequency-time diagram demonstrates that the VLF electric field signals detected here are undispersed rising impulses, typical of bursts detected in the shock, in other current layer regions of the sheath, and within the polar cusp at low altitudes [Scarf et al., 1972; Fredricks et al., 1973].

These current-driven instabilities generally develop when the scale length for the field gradient is of the order of $\delta$, the electron inertial length. If we assume that steep field gradients such as this were sporadically present at this time, it is clear that the 8-kbit/sec sampling rate was not adequate to resolve the actual gradients for the 1000-km/sec flow speed. Thus, in some regions the $|B|$ profile of Figure 8 may be aliased in the sense that intense higher-frequency fluctuations could have been present.

As Ogo 5 proceeded outward on November 1, 1968, the plasma flow and the field patterns gradually became more stable. Figure 9 shows that the ULF wave power, as measured by the de magnetometer, slowly decreased, and that the low-frequency peak became less evident. The curve labeled $C$ in Figure 9 shows a frequency spectrum intermediate between the extreme one of 1501-1521 UT and the normal (November 6 and October 27) magnetosheath spectral densities of Figure 5. However, since no interplanetary plasma data are available for this interval, we cannot tell whether this decrease in the magnetosheath noise was associated with a change in the solar wind or with the increasing distance of Ogo 5 from the cusp-sheath interface region.

**Discussion and Summary**

The November 1, 1968, storm was one of the largest geomagnetic disturbances of the solar cycle, and for an extended period in the midst of the event the solar cusp was at low enough magnetic latitude so that Ogo 5 instruments could make local measurements of cusp phenomena. The spacecraft also traversed the complex interface region between the magnetospheric cusp and the magnetosheath, but in evaluating the significance of these higher-altitude observations, it must be kept in mind that an intense storm was underway at the time. Thus it is possible that the results reported here are not typical for quiescent solar wind conditions.

Several spacecraft instruments detected a pair of apparent boundary crossings during the outbound pass. The first boundary at 1427 UT was primarily associated with an abrupt change in the magnetic field orientation and in the ULF power spectral density. At this point the total ion flux also jumped and the electron energy spectra changed form, but the VLF electric field spectrum merely started to vary in a gradual and continuous manner. The observed changes in magnetic field orientation, ULF power spectral density, and plasma characteristics at this boundary are very similar to the variations normally found at the magnetopause, and the appearance of magnetic wave power at relatively high frequencies after 1427 would not be expected if Ogo 5 had simply passed into a stagnant plasma region.

The second discontinuity, detected at 1456 UT, resembled a collisionless shock in many ways. Very intense electric field noise bursts were detected here, and on the upstream side, the average magnetic field was smaller, the average proton flux was higher, and the magnetic power spectral density was shifted toward higher frequencies, indicating that the ambient plasma flow speed had jumped. The limited plasma probe velocity measurements in this region are also consistent with the interpretation that Ogo had traversed a discontinuity resembling an attached shock.

If the November 1, 1968, transition region observations are typical of the low-latitude cusp-sheath interface conditions for quiet or moderately disturbed times, it can be concluded that wave-particle interactions at the upstream discontinuity (or attached shock) provide mechanisms for scattering magnetosheath plasma into the polar cusp. However, it should also be noted that these interactions modify the plasma distribution functions so that experimenters analyzing low-altitude cusp particle spectra should be cautious in comparing their measurements with simultaneous observations from magnetosheath plasma instruments.

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