OGO 5 OBSERVATIONS OF THE PHYSICAL PROCESSES OCCURRING IN THE DISTURBED POLAR CUSP AND THE CUSP-MAGNETOSHEATH INTERFACE

C. T. Russell a, R. W. Fredricks b, M. G. Kivelson a, M. Neugebauer c and F. L. Scarf b

aInstitute of Geophysics and Planetary Physics, University of California, Los Angeles, Calif., USA
bSpace Sciences Department, TRW System Group, Redondo Beach, Calif., USA
cJet Propulsion Laboratory, California Institute of Technology, Pasadena, Calif., USA

OGO 5 observations of the polar cusp on 1 November 1968 show that the north-south component of the interplanetary field exhibits control over, not only the location of, but also the physical processes occurring in, the polar cusp. When the interplanetary field was southward, the electron temperature in the polar cusp was lower and the currents were stronger than when the interplanetary field was northward. In addition, regions of apparently rapidly varying currents were encountered within the cusp, together with enhanced VLF electric fields. When the interplanetary field was northward, quasi-monochromatic Pe 1 waves close to but below the proton gyrofrequency were observed which were inconsistent with cyclotron resonant generation. Estimates of anomalous resistivity along field lines due to the electrostatic waves lead to estimates of field-aligned potential drops between OGO 5 (at ~3 R_e geocentric) and the ionosphere of the order of 2 kilovolts. When OGO 5 entered the magnetosheath near the cusp-magnetosheath boundary the fluxgate magnetometer recorded the highest level of turbulence that it had ever encountered in any region of space. One possible interpretation of these data is that the attached shock postulated by Walters was present at this time.

1. Introduction

Plasma measurements on a variety of spacecraft have shown the magnetosheath plasma penetrates from the magnetopause to the ionosphere in a thin arc above the dayside auroral oval [1—3]. This region, called the polar cusp by some and the cleft by others, is a permanent feature of most modern models of the magnetosphere and has been probed many times by both low altitude polar and highly eccentric orbiting spacecraft. Nevertheless, many of the properties of the cusp, many of the processes occurring within the cusp and the role of the cusp in magnetospheric dynamics remain unstudied or are subjects of controversy.

In this paper, we discuss measurements made by OGO 5, a three-axis stabilized spacecraft, during one set of multiple encounters with the polar cusp on 1 November 1968. While OGO 5 encounters with the polar cusp are few in number, the high temporal and amplitude resolution provided by the OGO 5 instruments, and the complement of instruments carried by OGO 5 provide information on the polar cusp not presently available from other spacecraft. We first review briefly the solar wind and magnetospheric conditions during these encounters and summarize previous OGO 5 findings; then we examine three separate topics: field-aligned currents in the polar cusp, turbulence in the cusp, and the cusp-magnetosheath interface.
2. Geomagnetic Conditions and OGO 5 Trajectory during the Cusp Encounters

As discussed by Russell et al. [3], a large sudden commencement geomagnetic storm began early on 31 October 1968. During the recovery phase of this storm, on 1 November, another sudden commencement occurred and a new main phase developed. The OGO 5 encounters with the cusp took place as the second main phase developed. The $Kp$ index was 8+ at this time. Solar wind plasma data were not available for most of the OGO 5 outbound pass. However, magnetosheath measurements were available from Vela 4B late in the pass, at which time the magnetosheath flow velocity ranged from 700 to 1000 km s$^{-1}$ and the density from 9 to 33 cm$^{-3}$. As will be discussed below the interplanetary magnetic field was alternately strongly southward and strongly northward. Fig. 1 shows the trajectory of OGO 5 in the dipole meridian as well as the expected field line geometry and the locations of two of the cusp encounters. At 1427 UT OGO 5 entered the magnetosheath.

![Diagram](image-url)
3. Previous OGO 5 Findings

The similarity of the fluxes and energy spectra of the suprathermal electrons measured by the JPL solar wind experiment to those of magnetosheath electrons has been used to identify the regions of suprathermal electron enhancements as encounters with the polar cusp. During these encounters, decreases in the magnetic energy density consistent with the presence of equal densities of magnetosheath protons were observed [3]. There were four encounters with the polar cusp spanning a range of local times from 1100 to 1400 LT. OGO 5 wave measurements have revealed that the polar cusp was quite turbulent with intense ULF magnetic and VLF electrostatic fluctuations [3, 4]. The ULF wave power was more intense transverse to the field than parallel to the field. The VLF electrostatic emissions were identified as being, in part, lower hybrid resonance noise, and possibly, in part, Buneman current driven instabilities. As noted in the initial survey of these data [3], the cusp moved equatorward when the interplanetary field was southward and poleward when it was northward. In later work [5], further dependences of the cusp on the north-south component have been examined. The average energy of the suprathermal electrons decreased for southward fields, and energetic electron fluxes ($E > 50$ keV) were present only for northward interplanetary fields. This latter observation suggests that cusp plasma was present on closed field lines. Further, the currents in the polar cusp weakened when the interplanetary field turned northward.

4. Polar Cusp Currents

There are two types of currents observed in the polar cusp: a broad diffuse current flowing essentially throughout the cusp [6] and narrow intense current filaments [7]. Low altitude measurements [8] appear to include contributions from both current types. Fig. 2 shows one-minute averages of the magnetic field during the first two cusp encounters in a field-aligned coordinate system ($Z$ along the average measured field and $Y$ azimuthal eastward). The internal geomagnetic field of approximately 1000 $\gamma$ has been subtracted from these data. The field-aligned component $B_z$ has been plotted (solid line) on the same scale as the deviation of the field $\Delta B$ from the predicted field strength (dashed line) for that position. There is close agreement between these two variables and the region of magnetic field depression is taken to be the region of enhanced proton flux. It does not show a one-to-one correspondence with the presence of suprathermal electrons as measured by the electron energy density shown on the bottom panel.

Sheets of field-aligned currents flowing on shells of constant $L$-value will cause magnetic perturbations in the azimuthal direction. The signature of two parallel but opposing sheets of current is a large perturbation of this type, a peak. In both cusp encounters 1 and 2A there are two such peaks. In encounter 2A, during which the interplanetary field was northward, the perturbation and hence the current was much weaker. We expect two current systems with field-aligned segments in the polar cusp region. We will loosely refer to these systems by the type of current closing them in the ionosphere: Pedersen currents and Hall currents. Merging causes a poleward flow of both closed and open field lines. Open field lines are “dragged” across the polar cap and closed field lines flow into this
region to replace them and eventually merge with the interplanetary field themselves. The ionosphere resists this motion. Pedersen currents flowing parallel to the electric field in the ionosphere exert a poleward force on the plasma to overcome the ionospheric drag. This current flows wherever field lines are moving and the ionosphere is resisting this motion. We would expect these currents to close in part along field lines if the resistance of the magnetospheric path is comparable with that of possible ionospheric paths. The perturbation field arising from this current system opposes the earth’s main field, effectively reducing the earth’s dipole field and allowing the magnetopause to move inward without a change in the solar wind dynamic pressure [9].

Hall currents will flow perpendicular to the applied electric field whenever there is a significant Hall conductivity, and can close along field lines when there is a gradient in the Hall conductivity. Such a gradient is expected in the polar cusp [10] and can lead to field-aligned sheets of current. We interpret our observations and those of other workers [6, 8] to be the closure of these Hall currents. A decrease in either the applied electric field, the Hall conductivity, or the Hall conductivity gradient could cause a weakening of these currents. The rapid motion of the polar cusp in response to changes in the north-south component of the interplanetary field suggests that the merging rate and hence the applied electric field decreased when the field turned northward. Finally, we note that,

Fig. 2. One minute averages of the magnetic field during the first two cusp encounters. The data are in a field-aligned coordinate system with Y azimuthal eastward and the contribution from the earth’s main field has been removed. The lower panel shows the energy density of suprathermal electrons every 19 seconds.
given a single Hall conductivity enhancement centered on the polar cusp, we expect a westward field perturbation. This agrees with previous work [6, 11]. Thus, perhaps the double twin current sheet structure should be viewed as the primary Hall closure system in the center bounded by two auxiliary currents poleward and equatorward.

Fig. 3 shows the second type of currents observed in the cusp. They are either filamentary or impulsive and last only seconds. Their amplitudes are not much

![Graph showing magnetic field data](image)

Fig. 3. High resolution magnetic field data (18 msec per sample) showing impulsive currents in the cusp, and ion cyclotron waves (lower right panel).

less than those in the large scale twin current sheets. However, they apparently are much narrower suggesting their current density is much more intense. Features such as these require observations from closely spaced satellites such as the planned mother/daughter mission (IME) before an unambiguous measure of thicknesses and hence their current density can be made.

5. Turbulence

The bottom right-hand panel of Fig. 3 shows ion cyclotron waves which were observed in the cusp only when the interplanetary field was northward and when the cusp plasma was observed on apparently closed field lines [5]. These waves are transverse to the field but have a compressional part. They do not have the characteristics of the pressure anisotropy-driven ion cyclotron instability, but instead may be generated by a current driven instability [12]. D'Angelo [13] has sought to explain the ULF fluctuations observed by OGO 5. He points out that
the various strong gradients in the cusp region would naturally lead to drift wave generation, but that, since the polar cusp plasma is expected to be streaming counter to the magnetospheric plasma, the Kelvin-Helmholtz instability should also occur. He considers the latter to be most consistent with the observed characteristics of the waves. However, as shown in the first three events of Fig. 3, much of this “turbulence” can be explained by “impulsive” field-aligned currents rather than waves. These “impulsive” currents are also accompanied by VLF electrostatic turbulence (see [7, Fig. 3]). The anomalous resistivity associated with this noise together with the observed currents could lead to a potential drop of the order of 2 kilovolts along the field line [7]. Such potential drops would significantly energize cusp plasma. Since such field-aligned currents are either narrow filaments or impulsive bursts, the associated electric fields would be filamentary or impulsive. In either case this would lead to a burst-like nature of precipitation in the polar cusp. An association of impulsive field-aligned currents and impulsive precipitation at low altitudes has been observed [14].

6. The Cusp-Magnetosheath Interface

At the top of Fig. 1 are shown the projections in the dipole meridian plane of one minute averages of the geomagnetic field in the region of the cusp-magnetosheath interface. The corresponding part of the orbit trace is shaded with a heavy

![Graph showing power spectra](image)

Fig. 4. Power spectra, summed over the three orthogonal directions, at the cusp-magnetosheath interface on 1 November 1968 and in the magnetosheath on neighboring orbits. A magnetospheric power spectrum is shown for reference.
line. High resolution data show that OGO 5 left the magnetosphere at 1427 UT and returned briefly from 1440 to 1442. The top panel of Fig. 1 shows that the magnetospheric field lines were oriented as expected during this interval, i.e. towards the earth and horizontally or slightly downwards. At other times, i.e. 1428—1439 and 1443—1500, the field assumed a variety of orientations. Examination of Explorer 33 interplanetary field data shows that these changes occurred in response to similar changes in the interplanetary magnetic field.

While the orientation of the magnetospheric and magnetosheath fields were rather as expected, the level of turbulence was not. Fig. 4 shows two power spectra obtained on this pass compared with power spectra in similar regions of the magnetosheath on other passes, and with a magnetospheric power spectrum at a similar radial distance. The wave power was two orders of magnitude higher on 1 November 1968 than on the control days. While 1 November was a disturbed day, this is a considerable enhancement of the power spectrum. Such enhanced turbulence is consistent with the suggestion made by Walters [15] of an attached shock at the cusp. On the other hand, Spreiter and Summers [16] have argued against the existence of such a region and instead postulate a contact discontinuity separating flowing magnetosheath plasma from stationary cusp plasma. Such a region should be turbulent also because of the Kelvin-Helmholtz instability but perhaps not as turbulent as behind a shock. We note that both Walters’ and the Spreiter-Summers’ models were proposed for closed magnetospheres, whereas merging is known often to play a significant role in the behavior of the magnetopause. Thus, while our data are consistent with the occurrence of an attached shock in this region, much more evidence is required for conclusive proof of its existence than we have on this one orbit.

7. Summary

The polar cusp plays a fundamental role in magnetospheric processes. Not only is the cusp an entry region of magnetosheath plasma and the source of daytime aurora, but field-aligned currents flow in the polar cusp communicating the stresses between the magnetopause and the ionosphere. During the very active period studied here broad Hall closure current sheets flow in the cusp, and there are filamentary or impulsive current structures in which the anomalous resistivity associated with VLF electrostatic emissions is capable of generating large potential drops along the field line. The interface region between the cusp and the magnetosheath is a complex, dynamic and turbulent region in which Walters’ attached shock may be present. In short, the polar cusp is a veritable plasma physics laboratory containing a broad spectrum of plasma physics phenomena.

Acknowledgments

This work was supported by the National Aeronautics and Space Administration under research grant NGL 05-007-004. Beneficial discussions of this work with F. V. Coroniti, T. E. Holzer and R. L. McPherron are gratefully acknowledged.
References