Correlated Electric Field and Low-Energy Electron Measurements in the Low-Altitude Polar Cusp

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Correlated electric field and low-energy electron measurements are presented for two passes of Hawk-eye 1 through the south polar cusp at 2000-km altitude during local morning. In one case the electric field reversal coincides with the boundary of detectable 5.2-keV electron intensities and the equatorward boundary of the cusp. In the other case the electric field reversal and the 5.2-keV electron trapping boundary coincide, but the equatorward edge of the cusp as determined from the presence of 180-eV electron intensities is 5° invariant latitude equatorward of the electric field reversal. We conclude that in the second case, electron intensities associated with the polar cusp populate closed dayside field lines, and hence the corresponding equatorward edge of these electron intensities is not always an indicator of the boundary between closed dayside field lines and polar cap field lines.

INTRODUCTION

The entry of magnetosheath plasma on dayside field lines just poleward of the trapping boundary and its penetration down to the ionosphere have been established at high altitudes by Frank [1971] and Russell et al. [1971] and at low altitudes by Frank and Ackerson [1971], Heikilla and Winningham [1971], and Maynard and Johnstone [1974]. Since the cusp marks the transition from dayside field lines to polar cap field lines, the polar cusp and its ionospheric projection, the midday aurora [Heikilla et al., 1972], have been used to infer changes in the earth's magnetic field configuration [Akasofu, 1972a, b; Yasuhara et al., 1973; Kivelson et al., 1973]. Similarly, the flow of low-altitude thermal plasma at high latitudes is the projection of the earth's magnetic field line motion at high altitudes and is also responsive to the configuration of the magnetosphere. Low-altitude measurements of electric fields by satellite-borne double probes [Cauvin and Gurnett, 1971; Heppner, 1972a] and by barium clouds [Wescott et al., 1969] have established that the high-latitude plasma convection generally consists of antisunward flow over the polar cap, an abrupt reversal in the east-west direction of flow at the equatorward boundary of the polar cap, and a sunward flow equatorward of the reversal. The flow speed generally peaks near the reversal. Simultaneous plasma and electric field measurements on the dayside of the polar cap, near the polar cusp, were first presented by Gurnett and Frank [1973], using data from the Injun 5 satellite. They found that the convection reversal occurred near the low-latitude boundary of the cusp plasma, although there was considerable uncertainty in the exact relationship, since the spatial resolution of the measurements was comparable to the width of the polar cusp. Heelis et al. [1976], using ion drift detectors, have obtained vector measurements of the convection velocity over the polar cap. Their measurements confirm the existence of abrupt velocity reversal on the flanks of the polar cap. However, they also showed that near noon the flow in the polar cusp is antisunward, and instead of reversing the velocity field rotates so that the component of flow normal to the low-latitude boundary of the polar cap is finite across the boundary. Substantial dawn-dusk components to the plasma flow were also observed near the polar cusp.

This paper presents simultaneous electric field and plasma measurements from the Hawkeye 1 satellite at low altitudes over the southern polar cap. The primary objective of this study is to further investigate the relationship of the plasma flow to the spatial structure of the polar cusp plasma distribution by using the improved spatial resolution of the Hawkeye 1 measurements compared to the earlier Injun 5 results.

INSTRUMENTATION

Hawkeye 1 was launched on June 3, 1974, into an elliptical orbit with an apogee of 21 Re over the northern polar cap and a perigee of 1800 km over the southern polar cap. The instrumentation on board consists of a complement of magnetic field, electric field, and particle detectors designed to study the properties of the polar cusp.

The electric field antenna is a copper-beryllium cylinder with a tip-to-tip length of 42.45 m and a diameter of 0.67 cm. The inner 30.2 m of antenna are insulated, leaving two exposed probes of 6.1-m length at each end. Static electric fields parallel to the antenna are obtained by measuring the difference in the floating potential of each probe, using a voltmeter with an input impedance of 10^15 Ω. To determine the electric field in a fixed frame of reference, the v x B potential resulting from the spacecraft's motion through the earth's magnetic field must be subtracted from the electric field measured in the spacecraft frame of reference. Corrections for slow changes in the effective antenna length are also included. At high altitudes over the northern polar cap, photoelectrons of spacecraft origin substantially modified the ambient static electric field. Consequently, the electric field data reported here were measured while the satellite was at low altitudes over the southern polar cap.

Since Hawkeye 1 is spinning with the electric antenna axis oriented perpendicular to the spin axis, the measured antenna potential difference is a sinusoid in time. The spin period is 11.009 s. Approximately 12 samples of the potential difference between the two probes are telemetered each spin. A sinusoidal least mean squares fit is made to the 12 samples to obtain the phase and amplitude of the signal. Because of a failure of the attitude determination system about 3 months after launch the absolute orientation is determined by comparing the on-board magnetic field with a theoretical model of the earth's magnetic field. Figure 1 indicates the reference system used to analyze the signal and to infer the electric field in three dimensions. The z axis is the spacecraft spin axis. The
Fig. 1. The reference frame for calculating the vector electric field in the plane perpendicular to the local magnetic field. The projection of the local magnetic field onto the spin plane is defined as the $x$ axis.

$x$ axis is the projection of the earth’s magnetic field onto the spin plane as measured by the on-board magnetometer. The electric field measured is the projection of the electric field vector onto the spin plane of the antenna. The phase of the sinusoid is referenced to the $x$ axis so that the $E_x$ and $E_y$ components are calculated from the sinusoidal fit once each spin. The component $E_z$ is calculated assuming that there are no electric fields parallel to the local magnetic field. From the relation $\mathbf{E} \cdot \mathbf{B} = 0$ with $B_z = 0$ it is seen that $E_z$ is given by $-E_x B_x / B_z$. Once the spin axis direction is known, the total electric vector is transformed into an earth-fixed frame of reference by assuming that the measured magnetic field is in the same direction as the reference field [Cain and Langel, 1968]. When the magnetic field is nearly parallel to the spin axis, the coordinate system orientation is susceptible to small errors in the measured magnetic field. For this reason, situations where the magnetic field is within $15^\circ$ of the spin axis have been eliminated from consideration.

The particle detectors on Hawkeye 1 consist of a Lepeeda (Low-Energy Proton-Electron Differential Energy Analyzer) that measures the directional differential intensities of electrons and protons from $50 \text{ eV}$ to $50 \text{ keV}$ in directions perpendicular to the spacecraft spin axis and a thin-windowed Geiger-Mueller tube that responds primarily to electrons with energy greater than $45 \text{ keV}$. In the Ramp mode a complete electron and proton spectrum is made every $11.5$ s over the energy range $100 \text{ eV}$ to $30 \text{ keV}$. The Hawkeye spin axis is nearly parallel to the ecliptic plane, and consequently, the Lepeeda samples a pitch angle range of up to $120^\circ$ over the southern auroral zone.

Over the south polar cap the telemetry signal from Hawkeye 1 is received at Orroral, Australia. This limits the coverage to a maximum invariant latitude of $-83^\circ$. The high-latitude termination of the data presented herein is the result of Hawkeye passing below the horizon for telemetry reception at Orroral.

OBSERVATIONS

The convection velocities measured along the Hawkeye 1 orbit on day 69, March 10, 1975, are shown in Figure 2 projected as viewed looking along the magnetic field vector. The velocity vector, calculated from $\mathbf{E} \times \mathbf{B} / \mathbf{B}^2$ in an inertial frame of reference, is plotted once per spin. The lines representing the velocity vector are plotted outward from the satellite position in magnetic local time and invariant latitude. Uncertainties and variations in the effective length of the antenna limit the instrument accuracy to about $0.5 \text{ km/s}$. For this pass, telemetry coverage begins at $2050 \text{ UT}$, and the spacecraft travels from about $79^\circ \text{ INV}$ and $1100 \text{ hours MLT}$ to $60^\circ \text{ INV}$ and $0900 \text{ hours MLT}$. Two zones of intense convection are present during this period. From $79^\circ \text{ INV}$ to $71^\circ \text{ INV}$ the velocity vectors have a primarily antisunward direction with peak magnitudes in excess of $4 \text{ km/s}$. From $71^\circ \text{ INV}$ to $68^\circ \text{ INV}$ a narrow zone of westward flow occurs with magnitudes similar to the polar cap flow. Equatorward of $68^\circ \text{ INV}$ a region of weaker flow is evident with an average antisunward direction. On this pass the velocity field rotates nearly $90^\circ$ in one spin ($11$ s) at $71^\circ \text{ INV}$ between the two zones of intense flow.

Differential electron intensities for this pass are plotted in the lower two panels of Figure 3 for $180 \text{ eV}$ and $5.2 \text{ keV}$. The electron flux for energies greater than $45 \text{ keV}$ is plotted in the top panel. The $180 \text{ eV}$ electron fluxes indicate a narrow intense event at $2053:25 \text{ UT}$ and a broader peak at $2055:00 \text{ UT}$. The $5.2 \text{ keV}$ record shows no fluxes above threshold before $2054:50 \text{ UT}$. A small peak occurs at $2055:00 \text{ UT}$ coincident with a distinct intensity maximum at $180 \text{ eV}$, and at $2056:00 \text{ UT}$ the flux rises above threshold for the remainder of the pass. The flux of electrons with energies greater than $45 \text{ keV}$ is always above threshold except for the first $20$ s of this pass. A gradual increase in the $E_z$ greater than $45 \text{ keV}$ electron intensities occurs between $2053:30 \text{ UT}$ and $2056:00 \text{ UT}$. At $2056:00 \text{ UT}$ the $E_z$ greater than $45 \text{ keV}$ intensities suddenly increase to $6 \times 10^6 \text{ electrons (cm}^2 \text{ s sr})^{-1}$ followed by a slow increase until $2100:00 \text{ UT}$. The location of the electric field reversal is indicated by a vertical line at $2255:35$. Since the reversal occurs in one spin, the temporal resolution for the electric field reversal determination is $\pm 6 \text{ s}$. The reversal separates the $180 \text{ eV}$ fluxes over the polar cap from the equatorward $5.2 \text{ keV}$ fluxes associated with the outer zone.

To identify the origin of the intense $180 \text{ eV}$ fluxes, two particle spectra are shown in Figure 4 from measurements made at $2053:25 \text{ UT}$ and $2054:45 \text{ UT}$. Both spectra show a peak near $200 \text{ eV}$, which is consistent with a magnetosheath...
The convection velocity measurements for day 263, September 20, 1974, are shown in Figure 5. The plasma flow over the polar cap during this pass is primarily east-west, but two distinct zones of sunward and antisunward convection are apparent. From 83° INV to 76° INV, plasma flows toward the east with a small component in the antisunward direction. The flow reverses, within one spin of the spacecraft, at 76° latitude, followed by westward flow with a component in the sunward direction until 67° INV. Equatorward of this point the convection velocity is less than 1 km/s in the antisunward direction.

For this pass, Figure 6 shows the differential electron intensities at 180 eV and 5.2 keV in the lower two panels and the integral electron intensity above 45 keV in the upper panel. The fluxes of electrons greater than 45 keV begin to decrease at 2242 UT and continue to decrease until 2245 UT. A solar proton event during this period maintains the count rate at an equivalent intensity of $4 \times 10^9$ electrons (cm$^2$ s sr)$^{-1}$. The differential electron intensities at 5.2 keV gradually increase until 2244 UT and then decline to values corresponding to threshold at 2244:30 UT for the remainder of the pass. Between 2237 UT and 2242 UT the electron intensities at 180 eV slowly decrease to threshold intensities. At 2243 UT the 180-eV fluxes suddenly increase and remain elevated to at least 2246 UT. The average flux is about $5 \times 10^9$ electrons (cm$^2$ s sr)$^{-1}$, which is consistent with previous observations in the polar cusp. The electric field reverses within one spin period, and the time of the reversal is shown as a vertical line. On this pass the electric field reversal marks the trapping boundary for 5.2 keV electrons, while the 180-eV electron intensities are located within 5° of latitude on either side of the reversal.

Two electron spectra are presented in Figure 7 for periods during the intense 180-eV electron fluxes but on either side of the reversal. Above 1 keV the differential fluxes decrease as the spacecraft passes poleward of the electric field reversal. Below 1 keV and equatorward of the reversal, peaks in the spectrum are observed between 500 eV and 1 keV and between 100 and 200 eV. The spectral peaks are also observed poleward of the reversal, and in this case their relative intensities are reversed. The electron differential intensities below 1 keV for these cases.
are similar to those of the magnetosheath, although those for 2243:30 UT are somewhat lower than those usually found in the magnetosheath proper.

**Discussion**

The term polar cusp in most cases refers to a particular plasma distribution found at high latitudes which resembles the plasma found in the magnetosheath. The proton spectrum peaks between 1 and 2 keV. Electrons peak at energies less than 1 keV, usually between 100 and 200 eV, with typical fluxes of $10^4-10^5$ electrons $(\text{cm}^2 \text{s sr eV})^{-1}$. At low altitudes this plasma signature is usually located within a strip between 70° and 85° invariant latitude and extending from 0800 to 1600 MLT. The latitudinal width of the strip has been reported as small as 0.2° INV latitude and as large as 6° INV latitude. For the remainder of this discussion we will assume that there exists a distribution of plasma over the ionosphere with the above characteristics and that the low-energy electron records presented here measure the spatial extent of the cusp along the Hawkeye 1 orbit near 2000-km altitude. We have restricted ourselves to electron measurements, since the threshold for the rapid scan proton channel at 2 keV is $10^3$ protons $(\text{cm}^2 \text{s sr eV})^{-1}$, which is too large for typical proton intensities in the cusp to be detected. These proton intensities are surveyed with the slower digital accumulator section of the instrument.

For the two satellite passes presented here the electric field changes within one rotation period of the spacecraft or within 0.5° of INV latitude. This sharp boundary has been reported by both Cauffman and Gurnett [1971] and Heppner [1972b]. Heelis et al. [1976] have further resolved the polar velocity field, using ion drift detectors which indicate that there is a narrow region near noon in which the plasma flows across the polar cusp boundary. The velocity rotation on day 69 apparently is of this type.

The 5.2-keV electron population is observed on dayside field lines equatorward of the electric field reversal and the cusp. This population probably originates near the inner edge of the plasma sheet, then gradient drifts toward morning and conveys sunward. These electrons are located inside the magnetosphere, and their poleward boundary is within 1° (slightly equatorward) of the electric field reversal for both cases presented here. The close agreement of these two boundaries implies that the 5.2-keV electron intensities fall below the detector threshold because they are no longer durably trapped. Hence the 5.2-keV electron threshold boundary supports the premise that the poleward boundary of closed dayside field lines does not lie equatorward of the electric field reversal.

The $E_e > 45$ keV electron flux begins to decrease in both cases at a latitude equatorward of the cusp and electric field reversal. A solar proton event on day 263 prevents the Geiger tube from reaching threshold and maintains an equivalent background intensity of $4 \times 10^5$ electrons $(\text{cm}^2 \text{s sr eV})^{-1}$ over the polar cap. On day 69 the $E_e > 45$ keV flux is at the threshold of 50 electrons $(\text{cm}^2 \text{s sr})^{-1}$ only briefly at the beginning of the record in a region 10° poleward of the electric field reversal. Frank [1965], using a similar instrument at high altitudes in the morning sector, observes no clear cutoff of $E_e > 45$ keV electron intensities at altitudes beyond 15 $R_e$ within 30° of the equatorial plane. Winningham [1972] has found $E_e > 45$ keV electron fluxes inside the cusp at low altitudes, and Mediavilla et al. [1976] report seeing the polar cusp entirely equatorward of their instrumental threshold boundary for 40-keV electrons. At most the $E_e > 45$ keV intensity profile restricts the trapping boundary to be located somewhere in the region of the intensity gradient. This is consistent with the electric field and 5.2-keV electron observations.

On day 69 the cusp is located just poleward of the electric field reversal. This agrees with any model where magnetosheath plasma flows down to the ionosphere on field lines threading the magnetosheath or boundary layer. The observed width of the cusp is about 1° of invariant latitude which agrees with the estimate Frank [1971] makes at higher altitudes and is smaller than the measurements from Isis 1 at lower altitudes.

The 180-eV electron intensities for day 263 have equatorward and poleward boundaries of 71° INV and 81° INV. A 10° wide cusp is larger than any previously reported. The

![Fig. 6. Electron intensities for the pass shown in Figure 5. Again note the termination of the 5.2-keV electron intensities essentially coincident with the location of the electric field reversal.](image-url)
poleward boundary of the cusp in this case is not well defined
from the electron intensity profiles, and the true width of the
cusp may be somewhat smaller. The poleward fluxes may be in
part ionospheric projections of the boundary layer [Ogilvie et
al., 1971] or of the plasma mantle. Regardless of the correct
poleward boundary location the width of this example is sev-
eral times larger than the previous example and in closer
agreement with the results reported from Isis 1 if we use these
low-energy electron intensities as sole identification for the
polar cusp. Then the equatorward boundary of the cusp lies 5°
equatorward of the electric field reversal on field lines popu-
lated by 5.2-keV electrons. Clearly, these field lines are closed
dayside field lines.

Equatorward of the electric field reversal the 180-eV elec-
tron intensities are more uniform than those poleward of the
reversal. The single intense peak at 2245:15 has a maximum
width of 60 km in the lower ionosphere. Similarly narrow
events have been observed at sounding rocket altitudes by
Maynard and Johnstone [1974].

D’Angelo [1973] shows that earthward streaming protons in
the cusp are susceptible to the Kelvin-Helmholtz instability.
The resulting turbulence enhances cross-field diffusion and is
capable of transporting protons across 2° of latitude at the
Bohm diffusion rate. Electrons may diffuse somewhat faster if
they are not inhibited by ambipolar forces. The distribution on
day 263 is located 5° equatorward of the electric field reversal
and does not decay from a source, as would be expected for
cross-field diffusion. This mechanism may contribute to trans-
porting cusp plasma onto closed field lines, but it does not
appear to be the dominant process on day 263.

Paschmann et al. [1976] have investigated the polar cusp
near the magnetosheath, using particle detectors and magne-
tometers. They find that on closed dayside magnetic field lines,
equatorward of the estimated neutral line and adjacent to the
magnetosheath, there exists a region of plasma with density
and temperature equal to the density and temperature of the
magnetosheath but with variable flow velocity and direction;
they call this region the entry layer. The first example they
present has a narrow inner boundary and is sufficiently wide to
project into the area of low-energy electrons observed equa-
torward of the electric field reversal on day 263. This single
example is not conclusive, but it is consistent with the inter-
pretation that the low-energy electrons on closed field lines
during day 263 are the low-altitude projection of the entry
layer.

Conclusions

The two examples presented here are insufficient to make a
general statement on the relative locations of the trapping
boundary, the electric field reversal, and the low-altitude cusp,
but they do prescribe a minimum range of relative positions
for these structures.

In both cases the electric field reversal occurs within 1° of
invariant latitude poleward of the termination of measurable
5.2-keV electron intensities, and these two structures occur
poleward of the initial 45-keV electron flux decrease. The
electric field reversal probably represents the boundary be-
tween closed dayside field lines and field lines threading the
magnetosheath, the boundary layer, or the tail.

Electrons of magnetosheath origin populate field lines just
poleward of the electric field reversal and in some cases popu-
late field lines equatorward of the electric field reversal. The
width of the cusp varies from 1° to at least 6° of latitude at
2000-km altitude. The equatorward low-energy electron popu-
lation on day 263 may be an extension of the entry layer
reported by Paschmann et al. [1976] to low altitudes.

The equatorward boundary of the low-energy electron distribu-
tion does not always coincide with the low-latitude boundary
of the polar cap. We caution against interpreting the
equatorward termination of low-energy electron intensities as
the boundary between closed dayside field lines and polar cap
field lines.
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