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SIMULTANEOUS GROUND AND ROCKET BASED MEASUREMENTS OF ELECTRIC FIELDS AND CURRENTS IN AN AURORAL ARC

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SIMULTANEOUS GROUND AND ROCKET BASED
MEASUREMENTS OF ELECTRIC FIELDS
AND CURRENTS IN AN AURORAL ARC

by

Robert M. Robinson

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE

DOCTOR OF PHILOSOPHY

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HOUSTON, TEXAS

MAY, 1980
ABSTRACT

SIMULTANEOUS GROUND AND ROCKET BASED
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A Terrier-Malemute sounding rocket was launched into a stable, premidnight auroral arc. Among the instruments carried by the payload were a cesium vapor magnetometer, electrostatic curved-plate electron energy analyzers, and two sets of Langmuir double-probes. Simultaneous line-of-sight velocity and electron density measurements were made during the flight by Chatanika radar operating in an elevation scan mode in the magnetic meridian.

Data from the magnetometer indicated that a broad region of eastward current flowed within the diffuse aurora equatorward of the arc, while westward current flowed within the arc itself. The field aligned current was downward in the diffuse aurora and uniformly upward in a 100 km wide region which contained the arc. This current pattern suggests that the payload traversed the entire Region 1 field aligned current system. The narrowness of the current was probably due to the expansion of the auroral oval associated with the growth phase of a substorm which occurred one hour after the flight.

The double probe measured a 40 mV/m northward
electric field just equatorward of the arc. Within the arc the northward electric field was zero. The tangential component of the electric field was 7 mV/m and was constant across the arc boundaries. Since the electric field in the arc was not strong enough to account for the westward current measured by the magnetometer, the presence of a westward neutral wind was inferred. This westward wind is consistent with the difference between the meridional electric field measured by the double probe and the radar.

Differences in the east-west electric field measured by the two instruments could be accounted for by an upward drift of ions at 100 m/s within the arc. This ion current constituted half of the measured upward field aligned current within the arc, while the other half was carried by precipitating electrons.

The simultaneous measurements enabled the association of the aurora with large scale regions in the magnetosphere. They also allowed the construction of a self consistent perpendicular current system for the arc involving a time varying neutral wind. There was some discrepancy in the field aligned currents derived from the data. This was attributed to the arc's association with the Harang Discontinuity,
ACKNOWLEDGEMENTS

I would like to express sincere gratitude to my thesis advisor, Dr. H. R. Anderson, for his conscientious guidance and support during the course of this work. Simultaneous measurements such as those discussed in this thesis necessarily involve close cooperation between several investigators. Dr. R. R. Vondrak of SRI International provided the radar data and offered many helpful suggestions in interpreting the results. Dr. E. A. Bering of the University of Houston supplied the double probe data and several figures used herein. I also benefited from discussions with Dr. P. A. Cloutier and Dr. P. H. Reiff. I would also like to thank the faculty, staff, and students of the Rice University Space Physics Department for making my stay in Houston both stimulating and enjoyable.

This work would not have been possible without the continued support and understanding of my parents and my wife, Lesvia. My daughter, Gina, also provided a little (7 lbs., 5 oz.) extra incentive at a very crucial time.

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## CONTENTS

<table>
<thead>
<tr>
<th>CHAPTER</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Experimental Technique</td>
<td></td>
</tr>
<tr>
<td>2.1</td>
<td>Description of the Payload</td>
<td>6</td>
</tr>
<tr>
<td>2.1.a</td>
<td>Electron Spectrometer</td>
<td>6</td>
</tr>
<tr>
<td>2.1.b</td>
<td>Double Probes</td>
<td>8</td>
</tr>
<tr>
<td>2.1.c</td>
<td>Vector Magnetometer</td>
<td>9</td>
</tr>
<tr>
<td>2.2</td>
<td>Chatanika Radar Measurements</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>Experimental Results</td>
<td>14</td>
</tr>
<tr>
<td>3.1</td>
<td>Launch Conditions and Vehicle Performance</td>
<td>14</td>
</tr>
<tr>
<td>3.2</td>
<td>Electron Spectrometer Results</td>
<td>22</td>
</tr>
<tr>
<td>3.3</td>
<td>Double Probe Results</td>
<td>25</td>
</tr>
<tr>
<td>3.4</td>
<td>Magnetometer Results</td>
<td>28</td>
</tr>
<tr>
<td>3.5</td>
<td>Chatanika Radar Results</td>
<td>38</td>
</tr>
<tr>
<td>3.6</td>
<td>Electrodynamics of the Arc</td>
<td>44</td>
</tr>
<tr>
<td>4</td>
<td>Discussion</td>
<td>68</td>
</tr>
<tr>
<td>4.1</td>
<td>Relation of the Arc to the Outer Magnetosphere</td>
<td>68</td>
</tr>
<tr>
<td>4.2</td>
<td>Ionospheric Response</td>
<td>83</td>
</tr>
<tr>
<td>4.2.a</td>
<td>Horizontal Current Flow</td>
<td>83</td>
</tr>
<tr>
<td>4.2.b</td>
<td>Neutral Winds</td>
<td>86</td>
</tr>
<tr>
<td>4.2.c</td>
<td>Joule Heating</td>
<td>90</td>
</tr>
<tr>
<td>4.2.d</td>
<td>Field Aligned Currents</td>
<td>92</td>
</tr>
<tr>
<td>4.2.e</td>
<td>F-Region Hole</td>
<td>99</td>
</tr>
<tr>
<td>5</td>
<td>Summary and Conclusions</td>
<td>101</td>
</tr>
<tr>
<td>A</td>
<td>Radar Elevation Scan Measurements of Ionospheric Electric Fields</td>
<td>109</td>
</tr>
<tr>
<td>B</td>
<td>Comparison of Rocket and Radar Electric Field Measurements and Derivation of Neutral Winds</td>
<td>124</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td>133</td>
</tr>
</tbody>
</table>
CHAPTER 1

Introduction

Auroral phenomena in the high latitude ionosphere are the visible portions of electromagnetic interactions between two physically distinct and widely separated regions: the ionosphere and the magnetosphere. As such, the study of the aurora is particularly difficult, requiring simultaneous measurements over an extended region of space. In addition, the understanding of the complex interplay of particles and fields requires measurements of several ionospheric and magnetospheric parameters.

Initial studies were limited to ground-based measurements made by photometers, spectrometers and magnetometers. Beginning in the late 1950's, these techniques were combined with observations by rockets which carried instruments to detect precipitating particles associated with the aurora. These experiments verified, for example, that precipitating electrons in the energy range 1 to 10 kev were primarily responsible for auroral luminosity (McIlwain, 1960). Later rocket flights carried double probes to measure electric fields and magnetometers to detect perturbations caused by ionospheric currents. However, the small size of rocket payloads made it difficult to include enough instruments to simultaneously measure energetic particles, electric fields and ionospheric currents.
Rice University has flown a number of instrumented sounding rockets into auroral forms with varying degrees of success (Cloutier et al., 1970; Cloutier et al., 1973; Anderson and Cloutier, 1975; Sesiano and Cloutier, 1976). Each of these carried energetic particle detectors and a vector magnetometer. They showed that auroral arcs were associated with a pair of field aligned sheet currents with the upward directed sheet roughly coincident with the arc and a downward sheet current displaced to the north or south of the arc. Several theories for the formation of auroral arcs grew out of these observations (Atkinson, 1970; Ogawa and Sato, 1971; Sato and Holzer, 1973). However, ultimate verification of these ideas requires simultaneous electric field and current measurements in the aurora.

This thesis reports the results of a sounding rocket flight which simultaneously measured energetic particles, magnetic field perturbations, and electric fields in an auroral arc. In addition, to provide a certain degree of redundancy, Chatanika radar was operating during the flight in a mode which provided independent measurements of electric fields and currents in the arc. Some of the results obtained by comparing the simultaneous measurements are noted below.

1. The northward electric field measured by the double probe and the radar could be brought into agreement by the addition of a neutral wind.
2. The horizontal currents detected by the magnetometer were consistent with the rocket electric field measurements and the radar-derived conductivities provided a time varying neutral wind was assumed.

3. The differences between the rocket and radar westward electric field measurements indicated the presence of an upward ion drift within the auroral arc. This drift accounted for roughly half the upward field aligned current detected within the arc, while the other half was carried by the precipitating energetic electrons.

4. The field aligned current pattern measured by the magnetometer did not agree with that expected from the rocket-measured electric fields and the radar-derived conductivities.

The simultaneous measurements have also enabled some conclusions to be reached about the relationship of the aurora to the large-scale magnetospheric flow pattern. Typically, it has been very difficult to correlate features observed by high altitude satellites with auroral features in the ionosphere. Part of this difficulty arises from the inability to map satellite observations to low altitudes because of uncertainties in tracing magnetic field lines. Even when such mappings can be made the high speed of a satellite often obscures the small scale features which are apparent in the ionosphere.
For similar reasons, rocket measurements, though yielding high spatial resolution, cannot be easily mapped up into the magnetosphere. However, if the rocket measurements can be expressed relative to certain magnetospheric boundaries, then an accurate mapping may be possible. Such is the case in the present experiment because the payload fortuitously passed over several regions whose boundaries were discernible in the particle, electric field and magnetometer data. Some of the conclusions which came out of this study are listed below.

1. The auroral oval at the time of launch was expanded and narrow, a deformation possibly associated with a substorm which occurred one hour after the flight.

2. The arc was threaded by an upward field aligned current which flowed back into the tail of the magnetosphere along the boundary of the plasma sheet.

3. The arc was an inverted "V" event which was situated poleward of the trapping boundary and equatorward of the polar cap.

4. The upward field aligned current flowed into two adjacent plasma regimes, one tenuous, the other dense. Field lines from the arc were connected to the dense plasma region.

The following chapter describes the payload flown in this experiment, including a more detailed explanation of
those instruments which pertain directly to the present study. The radar technique will also be discussed in this chapter and in the Appendices, as these results are important in understanding the measurement of neutral winds and ion drifts. Chapter 3 will describe the launch conditions and present the results obtained by the various instruments. This chapter will also include an attempt to consolidate the independent measurements into a self-consistent model of auroral currents. Chapter 4 will discuss the main conclusions which can be drawn from this attempt and also discusses how the aurora was related to the large scale magnetospheric structure. Chapter 5 will summarize the results and discuss to what extent they can be generalized to other auroral arcs.
CHAPTER 2
Experimental Technique

2.1 Description of the Payload. A diagram of the payload is shown in Figure 2-1. It was launched upon a Terrier-Malemute, two-stage, solid propellant booster provided by the National Aeronautics and Space Administration. The rocket was launched toward magnetic north from Poker Flat, Alaska, on a trajectory which took it across field lines connected to an auroral arc at an altitude of about 300 km. The instruments included in the payload which relate most directly to the electrodynamics of the arc will be discussed in some detail below with particular emphasis on possible sources of error.

2.1.a Electron Spectrometer. The construction and calibration of this instrument is described in Feinberg (1978) and Pulliam et al. (1980). It consisted of two stacks of 11 electrostatic curved plate analyzers. The 11 analyzers in each stack had energy passbands which allowed detection of electrons with energies from 30 ev to 20 kev. One stack was mounted with its look-angle at 45° from the spin axis and the other stack had its look-angle at 135° from the spin axis. Stabilizing fins on the booster were angled to give the vehicle a spin rate of several revolutions per second. An attitude control system (ACS) was included to tip the payload spin axis to an angle of 45°
from the direction of the geomagnetic field. With the payload spinning and oriented at a 45° angle from the tail of the ambient magnetic field, the up-looking detectors would count particles with pitch angles from 0 to 90°, while the down-looking detectors surveyed particles with pitch angles from 90 to 180°. A similar mounting scheme was employed for proton detectors and Geiger-Mueller tubes which were also included on the payload. For this thesis, only the net energy flux and current carried by the precipitating particles are important. Since the protons and the very high energy electrons (>40 kev) carried very little net energy flux and negligible current, the data from these latter two instruments will not be discussed. The main errors in the electron detector measurements arise from preflight calibration. As we are mainly concerned here with the variation of energy flux over the trajectory these systematic errors have little effect. Results of the electron spectrometer experiment are discussed in considerable detail by Pulliam et al. (1980).

2.1.b Double Probes. The double probes for the payload were supplied by E. A. Bering of the University of Houston. They consisted of two pairs of spherical electrodes which were extended from the payload fore and aft to a separation distance of 3 meters. Besides measuring DC electric fields the probes were used in conjunction with
low and high frequency spectrum analyzers to detect
electric field fluctuations of frequencies from 10 to
200 kHz and from .2 to 10 MHz, respectively.

Fahleson (1967) has reviewed the double probe
technique for measuring electric fields. The directly
measured quantity is the potential difference between two
probes widely separated in the ambient plasma, but con-
ected via a high impedance voltmeter. The largest errors
in the double probe electric field measurements result
from the transformation of the fields measured in the
reference frame of the moving probes to a frame fixed with
respect to the earth. For a payload moving at 500 m/sec
the \( \vec{V} \times \vec{B} \) electric field is about 25 mV/m which is compar-
able to the ambient fields. However, accurate trajectory
and attitude information can minimize the errors caused
by this transformation. For this flight, trajectory
information was supplied by ground-based radar and attitude
information was supplied by both the vector magnetometer
and a star-sensing device. Typical errors for the double
probes are 1 mV/m for the north-south component and
2 mV/m for the east-west component.

2.1.c Vector Magnetometer. The magnetometer was a
cesium vapor type which responds to the total magnetic
field at the sensor. It was placed at the top of the pay-
load beneath an ejectable nose cone, as far away as possible
from the other instruments so that magnetic contamination
was kept to a minimum. The method by which the vector magnetic field is determined using a scalar instrument has been discussed by Cloutier (1967), Park (1970) and Sandel (1971). The vector field is expressed in a spherical coordinate system with the payload coning center as the polar axis. The field magnitude \( |B| \) and the polar angle \( \theta_c \) are computed directly from the magnetometer output vs. flight time. The azimuthal angle \( \phi_c \) is determined from the time between peaks in the magnetometer output. These times give a measure of payload spin frequency relative to the ambient field. This can be interpreted in terms of a change in field azimuth if the real spin frequency is known. The on-board star sensor supplied the required independent measurement of spin frequency. The magnetometer determines relative field magnitude to an accuracy of \( \pm 1 \) nT. Variations in the polar angle \( \theta_c \) and the azimuthal angle \( \phi_c \) are measured to an accuracy of \( .02^\circ \) and \( .05^\circ \), respectively. Absolute accuracies are limited due to (1) uncertainties in the unperturbed vector field (given by a spherical harmonic expansion of the terrestrial field), and (2) uncertainties in the magnetometer bias field (Robinson, 1979).

2.2 Chatanika Radar Measurements. For a two hour period ending 23 minutes before the flight and for a one hour period beginning 55 minutes after the flight, Chatanika radar was operating in a three-position mode. By making
line-of-sight velocity and electron density measurements at three different azimuths and at two different altitudes, such velocity measurements can be analyzed to yield large scale (i.e. spatially averaged) electric fields, neutral winds and currents. The uncertainty in these measurements is discussed in Kamide and Horwitz (1978) and Brekke et al. (1974). Since these three-position measurements are not crucial to the present study the uncertainties will not be discussed here. The three-position results can be used to indicate the geophysical conditions before and after the flight.

For 23 minutes before the launch until 55 minutes after the launch the radar operated in an elevation scan (ELSCAN) mode. For the present experiment the radar was fixed in azimuth in the magnetic meridian and scanned in altitude from an elevation of about 20° north to the zenith. One scan was made every 4 minutes. Line-of-sight velocity measurements were made every 15 seconds at 8 range gates. The range gates were approximately 50 km wide and were variably spaced to give measurements at 8 constant altitudes from 100 km to 500 km. Electron density measurements were also made every 15 seconds, but at range intervals of about 10 km.

The method by which electric fields are derived from line-of-sight velocity measurements is explained in Doupnik et al. (1977). Several variations of this technique were
used in the present experiment. These modifications are discussed in Appendix A. For now it is sufficient to note several important assumptions which are required to determine electric fields by the ELSCAN method.

(1) The velocities that are measured are line-of-sight velocities. Electric fields perpendicular to the magnetic field give rise to perpendicular ion drifts. The conversion of line-of-sight measurements to perpendicular velocities is usually made by assuming that the component of ion drift parallel to the magnetic field is zero. While this is often true, certain processes in the auroral ionosphere, for example, parallel electric fields and Joule heating, can give rise to significant parallel ion drifts (Bering, 1975).

(2) The radar cannot distinguish between a drift caused by an electric field and a drift caused by bulk motion of the neutral atmosphere. Viscous interaction between adjacent ionospheric layers and ion drag cause the ions to move with the neutrals even in the absence of any applied electric field (Rishbeth and Garriott, 1969). Without an independent measurement, the neutral wind velocity must be assumed to be negligible. A typical E-region neutral wind of 100 m/s can produce an error of 5 mV/m in the meridonal component of the electric field. This error is serious since it is often comparable to the size of the fields being measured. Some consolation is
provided by noting that a uniform neutral wind over the entire region will cause a constant offset in the measured electric field from its actual value. Variations of the field are still well represented.

(3) Because the transmitted pulse used by the radar is 320 μsec long, the measured velocity is a weighted average of the true velocity over a 96 km long section of the ionosphere. Although most of the contribution to the measured velocity comes from the center of the range gate, significant errors can arise if spatial gradients in electron density are large along the line of sight.

(4) Measurement of the meridonal component of the electric field by the ELSCAN method also requires accurate mobility coefficients. These quantities describe to what extent charged particles respond to an applied field. This response is given by $\mathbf{v} = \mathbf{E} \times \frac{\mathbf{B}}{B^2}$ if collisions are negligible (above 160 km). However, if collisions are important the mobilities depend on the collision frequencies in a complex way. Since collision frequencies are uncertain by a factor of 2, the computed mobility coefficients may contain large errors which propagate to the electric field measurements.

The above difficulties are discussed more quantitatively in the Appendices.
CHAPTER 3
Experimental Results

3.1 Launch Conditions and Vehicle Performance. Several hours after sunset at 1945 AST (Alaska Standard Time) a faint arc was observed north of Fort Yukon. To the south of the arc, stretching equatorward well past the zenith at Poker Flat, was a large region of diffuse aurora. As the evening progressed the arc remained stable and drifted slowly southward. The decision to launch was made when the arc was situated just to the north of the zenith at Fort Yukon. At the time of launch the arc's intensity was 20 kR in $\lambda$5577. A minute after launch it had faded to 15 kR but subsequently brightened and widened, so that as the payload passed through it, the arc was 40 km wide with an intensity of 40 kR. An all sky camera photo of the arc at this time is shown in Figure 3-1. After apogee the arc faded again and drifted to the south. Fifteen minutes later the arc broke up and at 0915 UT a 400 nT substorm began. Magnetic activity at the time of launch was moderate. $K_p$ for the three hour period preceding the flight was 3+. For the three hour period including the time of the flight $K_p$ was 3-.

Figure 3-2 shows the H component of the ground-based magnetometer data for March 9, 1978, for 7 stations located along the magnetic meridian. The time of the rocket flight
Figure 3-2
is indicated by the heavy line. North of Fort Yukon the stations recorded negative deflections while south of Fort Yukon positive deflections were recorded. This indicates that the arc may have separated a region of eastward current flow to the south from a region of westward current flow to the north. Such a feature is characteristic of the Harang Discontinuity, which was originally defined as the line that separates negative bay regions from positive bay regions (Harang, 1946). The Harang Discontinuity is slanted from southeast to northwest so that the local time of the transition from eastward current flow to westward current flow depends on latitude. A fixed observer sees the complete current reversal occur in 1 to 2 hours as the earth rotates beneath the stationary pattern. This behavior can be seen in the three position measurements made by Chatanika radar. Figure 3-3 shows the electric field measurements before and after the flight. Prior to launch there was a steady decrease in the northward and eastward components. Figure 3-4 shows the large scale current derived by combining these electric fields with height-integrated conductivities. The northeast current also decreases before 0800 UT. After 0900 UT the data is somewhat confused by the large northward electric field, probably associated with the substorm which occurred at this time. Excluding this field, the data are consistent with a shift from northeastward current to southwestward
current sometime between 0800 and 0930 UT.

The payload was launched at 0813:10 UT. An elevation view of the trajectory is shown in Figure 3-5 along with the approximate position of the arc as determined from all-sky cameras. The vehicle was launched toward magnetic north so that the plane of the trajectory was approximately the magnetic meridian plane. About 50 seconds into the flight a set of pyrotechnic devices was activated to release four doors and the nose cone exposing the various instruments. The spherical probes for the electric field experiment were extended at 0814:15 after which the high voltage power supply was turned on. The attitude control system worked properly and tipped the payload over to its desired orientation approximately 135° from the direction of the geomagnetic field. The vehicle reached apogee at 0818:02 as it passed over the auroral arc. At 0821:22 the arms holding the spherical probes were severed and a rotating shutter closed to protect the instruments during reentry. Descent speed was reduced by parachutes which were released at 0822:10 and the payload was recovered in good condition.

Telemetry worked properly for the entire flight. Radar tracking was also excellent enabling complete trajectory information to be computed for every second of flight.

Data from the electron detectors allowed energy
Figure 3-5
spectra to be computed over each 10 spins or about 4 seconds. The magnetometer provided vector magnetic field data for the same sampling period. Data from the double probes suffered to some extent from the accidental severing of the lower set of probes from the instrument electronics. With one pair of probes, only the potential difference perpendicular to the payload spin axis is measured. To get the component of $\vec{E}$ perpendicular to $\vec{B}$ thus requires the assumption that $E_{\parallel} = 0$. The validity of this assumption will be discussed in the next section.

3.2 Electron Spectrometer Results. Results of the electron spectrometer experiment have been discussed in detail by Pulliam et al. (1980). The data was analyzed to give the flux in each energy passband as a function of flight time. Field aligned fluxes of low energy ($< 1$ kev) electrons were observed at the edges of the arc and for two events within the arc. Monoenergetic peaks were apparent in the individual spectra at energies from 1 to 6 kev. Peaked spectra were observed only within the arc. Figure 3-6 is a plot of the net energy flux carried by the energetic electrons in the range 30 ev to 35 kev. The arc is distinguished by sharp gradients in the energy flux at 0817:30 and 0819:10. The diffuse aurora is associated with the uniform energy flux measured between 0814:30 and 0816:00. Notice that the net energy flux is always positive, meaning that more energy was deposited in the
ionosphere in the form of precipitating particles than was returned by backscattered particles. The net electron current parallel to \( \mathbf{B} \) was thus downward over the whole flight, constituting an upward conventional current.

Pulliam et al. (1980) analyzed the electron data and were able to reach some conclusions about the presence of parallel electric fields below the payload. Since both precipitating and backscattered electron fluxes were measured, the data could be used to test calculations designed to predict the measured return fluxes from the downgoing fluxes. On an earlier rocket flight, Reasoner and Chappell (1973) used a Fokker-Planck approach to show that the return fluxes measured by the rocket were too high to be attributed solely to scattering from the atmosphere. They postulated the existence of parallel electric fields below the rocket to account for the high return flux. The downgoing flux for the present flight was used in a program by K. Stammes and M. H. Rees (Stammes, 1979a,b) which takes advantage of the similarity between the electron precipitation problem and the problem of radiative transfer. The return fluxes computed in this manner showed good agreement with the measured return fluxes. An electric field of 1 mV/m acting over a distance of 100 km below the payload would alter the particle energy by 100 volts. Such a change in energy would affect the agreement with the calculations of Stammes and Rees,
Thus, these results argue against the presence of significant parallel electric fields below the payload.

The success of these calculations made it possible to test the model proposed by Evans (1974) in which the precipitating electron energy spectra can be reproduced by acceleration of a Maxwellian plasma through a parallel potential drop at some distance above the ionosphere with subsequent scattering off the atmosphere and reflection from the potential barrier. After about 10 successive bounces the calculated energy fluxes converge to values very similar to those observed. The initial electron energy distribution above the potential barrier is obtained by fitting a Maxwellian to that part of the observed spectrum above the energy peak. If the peak occurs at an energy $eV_o$ then the potential drop through which the electrons have fallen is given by $V_o$. The ability to predict the entire electron energy spectrum in this manner verifies the accuracy of the radiative transfer technique and lends support to the conclusion that no large parallel electric fields existed below the rocket. This point is important because the assumption $E_{||} = 0$ is required to get perpendicular electric fields from the double probe data.

3.3 Double Probe Results. Figure 3-7 shows the northward and eastward electric fields measured by the double probe with the assumption that the parallel component of $\vec{E}$ is
small. Two electric field measurements were computed for each spin of the payload. Some of the fluctuations in the data are due to random noise; however, some are real and probably associated with electromagnetic waves in the plasma. These are found to occur in regions where there are large gradients in energetic particle flux. Examples can be seen at 0819:02 and 0820:50. These times correlate well with similar perturbations in the magnetometer data, thus confirming the association of the electric field fluctuations with electromagnetic waves. A detailed discussion of these waves is outside the scope of the present work.

By comparing Figure 3-7 with Figure 3-6 (also, see Figure 4-1), it is apparent that the northward electric field is anticorrelated with the energetic particle flux. This is true even on a scale of at least 2 km as can be seen by comparing the features connected by dotted lines in Figure 4-1. This behavior is fairly common (Aggson, 1968; de la Beaujardiere et al.) and was predicted by Bostrom (1964) as resulting from the polarization of the electric field within the enhanced conductivity region produced by precipitating particles. The northward electric field is thus maximum in the depressed precipitation region south of the arc; the field is shorted out completely within the arc. The anticorrelation breaks down in the low precipitation region north of the arc where the northward electric field remains small.
Note that the eastward electric field seems to be correlated with the energy flux. However, this is probably a result of the orientation of the arc. From all-sky camera photos it was found that the arc was aligned from southeast to northwest at an angle of 15 to 20 degrees from magnetic east-west. This orientation suggests a more logical coordinate system for discussing electric fields and currents. When expressed in such a system it is found that the electric field component tangential to the arc is about 7 mv/m and is constant through the arc. This is consistent with the observed uniformity of the arc in the east-west direction. Thus the requirement \( \nabla \times \mathbf{E} = 0 \) ensures continuity of the tangential component of \( \mathbf{E} \) across the boundaries of the arc. Because the orientation of the arc was variable over the time of the flight, the arc-oriented coordinate system was not used in the data reduction and will not be used in the remainder of this thesis.

3.4 Magnetometer Results. The total magnetic field measured by the magnetometer over the trajectory was subtracted from a model of the terrestrial field given by a spherical harmonic expansion. Three expansions were used: IGRF (Trombka and Cain, 1974), IGS (Barracough et al, 1975) and AWC (Peeble and Febbiano, 1976). All three expansions gave values along the trajectory differing by no more than 2 nT. The expansions are determined by harmonic analysis of magnetic field data taken at a
multitude of points over the surface of the earth. Since the data are time averaged, the expansions filter out rapid changes in the terrestrial field due to transient ionospheric and magnetospheric currents. Thus the difference between the field measured by the magnetometer and that given by the expansion represents changes in the field due to ionospheric currents. The quantity \( \Delta B = B_{\text{measured}} - B_{\text{expansion}} \) is shown in Figure 3-8. Note that large perturbations occur at the beginning and the end of the flight. This is because ionospheric conductivities peak at about 120 km altitude so that most currents flow within a layer perhaps 40 km thick centered at this height. Once above the current layer the perturbation of the magnetic field drops off sharply in agreement with the variations shown in Figure 3-8.

Figure 3-9 is the angle measured by the magnetometer between the payload coning center and the ambient magnetic field. The uniform decrease in this angle \( \theta_c \) over the flight is probably due entirely to the change in the dip angle of the magnetic field as the payload moved northward. The rate of change of this angle is not consistent with that given by any of the field expansions. This discrepancy has been discussed by Robinson (1979) and was found not to be due to ionospheric current flow. In addition, there are no significant deviations in \( \theta_c \) which correspond to the perturbations in \( \Delta B \) at the beginning and the end.
of the flight. The only apparent deflection in $\theta_c$ occurs at 0817:15 but is only about $0.07^\circ$.

The other angle specifying the vector magnetic field is the azimuthal angle $\phi_c$. Since this angle is computed from small differences between the spin frequency measured by the magnetometer and that measured by the on-board star sensor, only variations in $\phi_c$ are actually determined. The change in $\phi_c$ over the flight is shown in Figure 3-10. The spin frequency measured by the magnetometer is not equal to the real spin frequency when the azimuth of the field changes during a spin. With the payload spin axis in the magnetic meridian plane this occurs only when the field has been deflected in the east-west direction. Field aligned sheet currents extended in the east-west direction produce just such a perturbation. If infinite sheet currents are assumed, the intensity of the current in the sheet is related to the rate of change of $\phi_c$ according to (Robinson, 1979).

$$J_{||} = 0.06 \frac{\Delta \phi_c}{\Delta t} \frac{\cos \beta}{\sin(\beta + I)} \text{ amps/m}^2 \quad 3-1$$

Here $\beta$ is the angle between the payload velocity vector and the horizontal and $I$ is the dip angle of the magnetic field.

Equation 3-1 cannot be used if $\beta \sim -I$. This situation corresponds to times in the flight during which the pay-
load is moving parallel to the field line in which case no change in $\phi_c$ can be measured although field aligned current may be flowing. Applying Equation 3-1 to the variations in Figure 3-10 yields the following field aligned current flow pattern. From 0814:30 to 0815:55 the flow was downward with a magnitude of $5 \times 10^{-6}$ A/m². From 0815:55 to 0819:20 the flow was upward with an average intensity of $4 \times 10^{-6}$ A/m². After 0819:20 Equation 3-1 breaks down. However, the small change in $\phi_c$ in this region indicates a possible downward field aligned current. The magnitudes of these currents are uncertain by perhaps 50% due to uncertainties in the real variation of the field. The changes in slope at 0815:55 and 0819:10 are less sensitive to these uncertainties so that it is more accurate to conclude that the current after 0815:55 was about $9 \times 10^{-6}$ A/m² upward relative to the flow earlier in the flight. At 0819:20 there is another discontinuity of about $4 \times 10^{-6}$ A/m². This latter discontinuity coincides very well with the northern edge of the arc.

Perturbations in $\phi_c$ can also be caused by north-south horizontal current flow. However, since these currents flow in the E-region the payload was already above the current layer by 0814:30 when the magnetometer signal stabilized. Thus, the variations in $\phi_c$ cannot be due to horizontal currents. A similar explanation applies to the end of the flight since the magnetometer signal
was lost after 0821:22 when the payload was still above 150 km. The absence of any apparent variations in the angle $\theta_c$ can also be attributed to the same problem. The lack of reliable magnetometer data for low altitudes was primarily due to the trajectory being much higher and shorter than anticipated. This was presumably due to improper wind weighting of the rocket at launch.'

Since effects of horizontal currents are not apparent in the $\phi_c$ and $\theta_c$ profiles, the only information available about the nature of these currents is the $\Delta B$ profile. Assuming east-west symmetry, changes in total field magnitude are caused only by east-west current flow. These east-west electrojets can be modeled by assuming filamentary currents flowing in the E-region. A first attempt at modeling is shown in Figure 3-11. The solid line is the magnetic perturbation caused by a current system which has an eastward electrojet south of the arc and westward electrojet within the arc. The current in the electrojets in this model increased toward the time of apogee and decreased thereafter. This time variation was made to correspond roughly to the observed variation in arc brightness which is usually accompanied by conductivity changes. Also, since the arc drifted southward at 200 m/s after 0819, the model current system was made with a similar motion. In Figure 3-11 a constant offset of 7 nT has been added to the data. This is permitted
since the magnitude of the field measured by the magnetometer is uncertain by more than this amount due to errors in precalibration of the applied bias field.

The modeling procedure involves varying the strengths of 36 current filaments spaced at 10 km intervals. Currents flowing equatorward of the arc were placed at an altitude of 125 km, while those in the arc flowed at 115 km. This was done to simulate the enhanced ionization at lower altitudes owing to particle precipitation in the arc. Since the payload was above the E-region for most of the flight, the resulting magnetic perturbation is relatively insensitive to the height at which the currents flow. For the same reason, the spatial resolution of 10 km for the current filaments is not a serious drawback.

The current system derived in this manner is by no means unique. However, in the course of the modeling several very definite trends emerged as to the nature of the east-west current flow. These are summarized below.

1. A time independent model does not reproduce the observed variations.
2. Most of the eastward electrojet flowed in the region just equatorward of the arc. The westward electrojet flowed within the arc.
3. The integrated current in the eastward electrojet was about 25,000 amps. The maximum current density in the eastward electrojet was about
.5 A/m. The integrated current in the westward electrojet was also about 25,000 amps, with a maximum current density of .6 A/m.

4. The current system drifted southward with the arc.

In Section 3.6 the simultaneous electric field and conductivity measurements are used to put further restrictions on the model current system.

3.5 Chatanika Radar Results. Chatanika radar line-of-sight velocity data were combined with height integrated mobilities in the manner described in Appendix A. The electric field measurements were obtained for each 20 km interval from the radar zenith to 240 km north. In order to simplify the following discussion the region under the trajectory will be divided into flux tubes which are 20 km in north-south width, but extended along the arc in the east-west direction. The flux tubes are numbered beginning with flux tube 1 which lies within the range 0 to 20 km (Figure 3-5).

The three elevation scans made during the flight yielded three electric field measurements for each flux tube. These measurements were interpolated to the time at which the payload passed through the given flux tube. The open circles in Figure 3-12 show the electric field measurements obtained in this manner as a function of horizontal distance north of the radar. The solid line in this figure represents the electric field values measured
by the double probe. The latter measurements, originally
given as a function of flight time, were converted to
horizontal distance by projecting the values at the
position of the payload down along field lines to the
120 km level. The uncertainties in this projection do not
amount to more than a few kilometers. This mapping, of
course, requires the assumption that there is negligible
potential drop along the field line. Figure 3-12 should
not be viewed as the ionospheric electric field profile
at a certain instant in time since the values plotted
for any particular flux tube are those that existed in
that flux tube at the time the payload passed through it.

It is apparent from Figure 3-12 that there are sig-
nificant differences between the rocket and radar electric
field measurements, especially in the north-south component.
The differences, which are maximum in flux tube 8, are too
large to be explained by temporal changes in the field.
Also, as explained in Appendix B they are too large to be
the result of errors in the ion mobilities.

To explain the differences in the northward electric
field measurements, a wind with southward and/or west-
ward components is required. A large scale neutral wind
should produce an almost constant offset between the real
electric field and that measured by the radar. The
differences shown in Figure 3-12 do not appear to be a
result of such a constant offset. However, the radar
measurements are distorted because of the 96 km averaging of the velocities. This distortion is especially serious in flux tube 8 near which there are large spatial gradients in electron density. The line-of-sight velocities are thus weighted heavily toward the high density region to the north. Since southward drifts prevailed in the arc, this weighting reduces the measured northward drifts in flux tubes 7 and 9. Appendix B presents an alternate method of comparing rocket and radar measurements which circumvents this difficulty. The results of this comparison show that a uniform neutral wind can indeed bring the two sets of measurements into agreement. In a coordinate system where $x$ is eastward and $y$ is northward the components $U_x$ and $U_y$, of the required wind must satisfy the relation

$$-U_x B = \frac{(1-k_2)U_y B}{k_1} = 15 \text{ mV/m} \quad 3-2$$

Within the arc the mobilities $k_1$ and $k_2$ are .188 and .060, respectively. A southward wind of 55 m/s or a westward wind of 280 m/s is necessary to make the rocket and radar measured electric fields consistent.

These numbers should be regarded as only very crude estimates. Appendix B discusses the range in the coefficients $k_1$ and $k_2$ allowed by a factor of 2 variation in the ion-neutral collision frequency. In estimating the wind,
however, we are again aided by the simultaneous current measurement supplied by the magnetometer. The neutral wind, when combined with the rocket measured electric field, should yield a current strong enough to produce the perturbations measured by the magnetometer. This comparison will be made in Section 3.6.

Returning to Figure 3-12, a difference in the east-west electric fields measured by the rocket and the radar is also apparent. The only assumption required in the radar measurement of this component of the electric field is that the parallel component of ion drift is negligible. In the upper part of Figure 3-13 $V_{\perp}$, is the perpendicular velocity computed from the line-of-sight velocity assuming $V_{\parallel} = 0$. $V_{\perp}$, is the perpendicular velocity for $V_{\parallel} \neq 0$. In these equations, $\theta = 180-\beta-I$ where $\beta$ is the elevation angle of the radar and $I$ is the dip angle of the magnetic field. Defining $E_{\text{radar}} = -V_{LS}B/\sin\theta$ as the electric field measured by the radar assuming $V_{\parallel} = 0$ and $E_{\text{rocket}} = -V_{\perp}/B$ as the real electric field, then $V_{\parallel}$ can be expressed in terms of the difference between $E_{\text{rocket}}$ and $E_{\text{radar}}$. Performing this calculation for the differences shown in Figure 3-12 yields the parallel ion velocity profile shown in the bottom of Figure 3-12. There are no significant parallel ion drifts except in the region of the arc where the drifts are upward at about 100 m/s. Assuming an F-Region ion density of $10^5$/cc this drift corresponds to
If $V_{\parallel} = 0$, $V_{\perp,1} = \frac{V_{Ls}}{\sin \theta}$

If $V_{\parallel} \neq 0$, $V_{\perp,2} = \frac{V_{Ls}}{\sin \theta} - V_{\parallel} \cot \Theta$

Since $E_{W,\text{RADAR}} = -V_{\perp} IBI$

$V_{\parallel} = \frac{\tan \theta}{IBI} (E_{\text{RADAR}} - E_{\text{ROCKET}})_{\text{WEST}}$

![Graph showing PARALLEL ION VELOCITY, m/s versus PROJECTED HORIZONTAL DISTANCE, km. The graph includes data for flux tube 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12.](image)
an upward current of about 2 \( \mu \text{A/m}^2 \). Since the upward current carried by precipitating electrons was also about 2 \( \mu \text{A/m}^2 \), together the upward drifting thermal ions and the energetic electrons account for all of the parallel current measured by the magnetometer within the arc.

Figures 3-14 through 3-16 are electron density contour plots constructed from the radar data for the 3 elevation scans during the flight. The rocket echoes give the location of the payload for each scan. The maximum electron density in the arc was about \( 6 \times 10^5/\text{cm}^3 \). The absence of detectable ionization north of the arc is characteristic of the polar cap. One interesting feature which persisted throughout the flight is the electron density hole at 200 km just south of the arc. This hole is located within the low precipitation, high electric field region between the diffuse aurora and the discrete arc. Possible explanations for its occurrence will be discussed in Section 4.2.5. The three electron density contour plots show the stability of the arc during the flight. The only significant change resulted from the southward motion of the arc between the second and third scans.

3.6 Electrodynamics of the Arc. The radar, double probe and magnetometer measurements can be combined self-consistently to construct a model for horizontal current flow in the arc which is less ambiguous than models based
on any of the individual measurements alone. This section describes how such a model was developed. Before proceeding, it is helpful to briefly summarize the basic theory of ionospheric electrodynamics. The review here follows that of Brekke et al. (1974) and Bostrom (1964).

The current \( \vec{j} \) flowing in a plasma can be expressed as

\[
\vec{j} = n_e e (\vec{v}_i - \vec{v}_e)
\]

where \( n_e \) is the electron density, assumed equal to the ion density, and \( \vec{v}_i \) and \( \vec{v}_e \) are the ion and electron drift velocities, respectively. In the ionosphere above 90 km the collision frequency for electrons is much less than the frequency of gyration of the electrons about the magnetic field \( \vec{B} \). If an electric field \( \vec{E}_\perp \) is applied perpendicular to \( \vec{B} \) the electrons' guiding center drift velocity is

\[
\vec{v}_e = \frac{\vec{E}_\perp \times \vec{B}}{B^2}
\]

The electron drift would constitute a current in the \( -\vec{E} \times \vec{B} \) direction if not for the ions which also drift with the same velocity in the same direction. However, the ion-neutral collision frequency in the ionosphere is larger than the ion gyrofrequency. The ion motion
is thus impeded by collisions and the net electron flow constitutes a current called the Hall current. The ability of a plasma to sustain currents in the $-\vec{E} \times \vec{B}$ direction is described by the Hall conductivity $\sigma_H$ which is given by

$$\sigma_H = \frac{n_e e}{B} \left( \frac{\Omega_i^2}{\Omega_i^2 + v_i^2} - \frac{\Omega_e^2}{\Omega_e^2 + v_e^2} \right)$$

where $\Omega_{i,e}$ and $v_{i,e}$ are the ion and electron gyrofrequencies and collision frequencies, respectively.

Each ion collision results in the ion having a velocity which is zero on the average. Starting from rest the ion is momentarily accelerated in the direction of $\vec{E}$. If there are enough collisions this behavior results in a net drift of ions, causing a current to flow which is not compensated for by electrons since they move mostly perpendicular to $\vec{E}$. The ion current in the direction of $\vec{E}$ is called the Pedersen current and the coefficient describing the ability for this current to flow in a plasma is the Pedersen conductivity $\sigma_P$:

$$\sigma_P = \frac{n_e e}{B} \left( \frac{\Omega_i v_i}{\Omega_i^2 + v_i^2} + \frac{\Omega_e v_e}{\Omega_e^2 + v_e^2} \right)$$

Finally, if there is a component of $\vec{E}$ in the direction of $\vec{B}$, the ions and electrons will drift in opposite directions along $\vec{B}$, resulting in a current related to $E_{||}$.
by \( \sigma_o \), the direct or parallel conductivity:

\[
\sigma = \frac{n_e e}{B} \left( \frac{\Omega_i}{v_i} - \frac{\Omega_e}{v_e} \right) \tag{3-7}
\]

Combining these results the current in the plasma can be written as

\[
\mathbf{j} = \sigma_p \mathbf{E}_\parallel + \sigma_H \frac{\mathbf{E}_\perp \times \mathbf{B}}{B} + \sigma_o E_\parallel \tag{3-8}
\]

Note that in the limit of low collision frequency for both ions and electrons \( \sigma_p \) and \( \sigma_H \) both become zero and there is no component of current perpendicular to \( \mathbf{B} \). Since collisions are negligible above 150 km and the electron density is usually small below 100 km, most of the current flows in a layer between these two altitudes. Also, since \( \sigma_\parallel \) is much greater than \( \sigma_p \) and \( \sigma_H \) in this region, parallel components of the electric field are shorted out very quickly. Thus, normally

\[
|E_\parallel| \ll |E_\perp| \tag{3-9}
\]

The above expressions for the conductivities were derived from the ion and electron momentum equations expressed in the rest frame of the neutral atmosphere. If the neutrals have a bulk velocity \( \mathbf{U} \) relative to the earth, Equations 3-5 to 3-8 are still applicable, pro-
vided the electric field $\vec{E}$ is replaced by $\vec{E} + \vec{U} \times \vec{B}$. $\vec{E}$ is now the electric field measured by an observer in the earth's reference frame. The current flowing in the plasma perpendicular to $\vec{B}$ is thus given by

$$\vec{J}_\perp = \sigma_P (\vec{E} + \vec{U} \times \vec{B})_\perp + \sigma_H \frac{(\vec{E} + \vec{U} \times \vec{B})_\perp \times \vec{B}}{B}$$

3-10

The total current $\vec{J}_\perp$ flowing through a cross sectional area of unit width between 90 and 170 km can be determined from

$$\vec{J}_\perp = \int_{90}^{170} \vec{J}_\perp \, dz$$

3-11

Assuming $\vec{E}_\perp$ and $\vec{U}$ are independent of altitude, Equation 3-11 can be integrated to give

$$\vec{J}_\perp = \Sigma_P (\vec{E} + \vec{U} \times \vec{B})_\perp + \Sigma_H \frac{(\vec{E} + \vec{U} \times \vec{B})_\perp \times \vec{B}}{B}$$

3-12

where

$$\Sigma_P = \int_{90}^{170} \sigma_P \, dz \quad \text{and} \quad \Sigma_H = \int_{90}^{170} \sigma_H \, dz$$

Although the assumption that $\vec{E}_\perp$ is independent of height is probably justified, the same assumption for $\vec{U}$ is not, Rino et al. (1977). However, the difficulty in making observations of neutral wind velocity as a function of
altitude makes such an assumption necessary.

As mentioned above, currents flow perpendicular to \( \mathbf{B} \) in a plasma only by virtue of collisions between the current carriers and the neutral gas. As a result of these collisions energy is transferred from the ions and electrons to the neutral molecules. The Joule heat dissipated per cm\(^2\) column through the ionosphere is given by

\[
Q_J = \mathbf{J} \cdot (\mathbf{E} + \mathbf{U} \times \mathbf{B}) \quad 3-13
\]

Using Equation 3-12 for \( J \) gives

\[
Q_J = \xi_p (\mathbf{E} + \mathbf{U} \times \mathbf{B})^2 \quad 3-14
\]

Banks (1977) has shown that very often the energy dissipated by Joule heating in the ionosphere is comparable to or greater than the energy dissipated in the form of precipitating particles.

Knowledge of the horizontal current profile in the ionosphere also enables determination of the field aligned current structure. In a steady state situation the currents must satisfy

\[
\mathbf{v} \cdot \mathbf{j} = 0 \quad 3-15
\]

Using an orthogonal coordinate system in which \( \hat{x} \) is east,
\( \hat{y} \) is north and \( \hat{z} \) is upward along the direction of \( \hat{B} \),

Equation 3-15 can be written

\[
\frac{\partial j_x}{\partial x} + \frac{\partial j_y}{\partial y} = -\frac{\partial j_z}{\partial z} \quad 3-16
\]

This equation can be simplified by taking advantage of the uniformity of auroral arcs in the \( \hat{x} \) direction. With this assumption, Equation 3-16 becomes

\[
\frac{\partial j_y}{\partial y} = -\frac{\partial j_z}{\partial z} \quad 3-17
\]

Integrating Equation 3-17 from \( z = 90 \text{ km} \) to \( z = 170 \text{ km} \), and assuming \( j_z = 0 \) at 90 km gives

\[
\int_{90}^{170} \frac{\partial j_y}{\partial y} \, dz = -j_z \quad 3-18
\]

or using Equation 3-11,

\[
\frac{\partial j_y}{\partial y} = -j_z = -j_{||} \quad 3-19
\]

Strictly speaking, if the arc is not oriented exactly along magnetic east-west, the spatial derivative with respect to \( \hat{x} \) may not be zero. The correct expression for \( j_{||} \) would then involve the change in the component of \( \hat{j} \) perpendicular to the arc along a direction normal to the arc. However, for the present case the errors in
using Equation 3-19 are small compared to the errors arising from uncertainties in $E$, $U$, $E_p$, and $E_H$. Thus, Equation 3-19 involves taking derivatives of quantities which are poorly known and indirectly computed from the raw data. The Joule heating and field aligned currents may be in error by as much as 50%. However, emphasis is placed here on the spatial variation in these quantities rather than on the quantitative results.

The parallel current density computed from Equation 3-19 can be compared with the estimates of $j_{||}$ obtained from the east-west perturbations of the magnetic field as measured by the magnetometer.

In all the above equations $\vec{B}$ is considered known. A complete specification of ionospheric currents requires knowledge of $E_p$, $E_H$, $E_{\parallel}$, and $U$. In this experiment, $E_p$ and $E_H$ are determined from height profiles of the ionospheric electron density as measured by the radar combined with an atmospheric model. The electric field is known most accurately from the rocket double-probe and $J_X$ can be indirectly determined from the magnetic perturbations recorded by the magnetometer. In addition, as explained in Section 3.5, information about $U$ is obtained by comparing rocket and radar electric field measurements. Together the problem of modeling a current system becomes to a certain extent overdetermined. The following analysis attempts to determine the arc current system.
in a self-consistent manner.

The rocket electric field data were combined with the radar-derived conductivities to produce an east-west current profile using Equation 3-12 with \( \hat{U} = 0 \). The result is indicated by the open circles in Figure 3-17a. If this current pattern is assumed constant in time, the magnetic perturbation expected along the trajectory can be calculated easily by Ampere's law assuming the current flows in filaments. The change in \( \hat{B} \) computed in this manner was found to be too small by a factor of three. This deficiency can be demonstrated most easily by comparing these currents with the model currents that are necessary to account for the \( \Delta B \) profile. These are shown by the histogram in Figure 3-17a. The magnetic perturbation produced by this model is shown in Figure 3-17b. The offset, given in the upper right-hand side of the figure, is the constant field bias which must be added to the data to make the model and data overlap optimally as discussed in Section 3.4. The quantity \( \chi \) is defined by

\[
\chi^2 = \frac{1}{N} \sum_{j=1}^{N} \left( \Delta B_{\text{model}} - \Delta B_{\text{data}} \right)^2
\]

3-20

where \( N \) is the number of data points. The model shown in Figure 3-17a will be referred to as Model 1.

It is apparent that the current required to produce this model is much larger than the current calculated
29.007 ELECTROJET MODEL 1
19000-30000 AMPS EAST
19600 - AMPS WEST
U WEST = +115 M/S
U SOUTH = +20 M/S
V DRIFT = 100 M/S SOUTH

Figure 3-17a

Figure 3-17b
from Equation 3-12 with $\tilde{U} = 0$. The discrepancy here is too large to be explained solely by errors in the conductivity. A more satisfactory explanation would be to assume a westward neutral wind. Possible magnitudes of the westward wind which are required to account for the difference between the radar and rocket electric field measurements are shown in Table B-1. The currents computed using a westward wind of 115 m/s are shown by x's in Figure 3-17a. Although the westward electrojet is enhanced the eastward electrojet is diminished so that the addition of such a wind does not bring the currents up to the required magnitude.

The only remaining possibility is that the time dependence used in Model 1 does not accurately represent the real variation in current during the flight. This can be understood by noting that the eastward and westward electrojets have opposite effects on those parts of the trajectory at which the payload was located at the beginning and end of the flight. In particular, the eastward electrojet south of the arc had to be made very large in order to cancel the effects of the westward electrojet to the north. A second model, Model 2, was created with this in mind. In this model, as in Model 1, the eastward electrojet increases toward apogee then decreases again. However, in Model 2 the westward electrojet increases uniformly over the flight from an integrated current of
0 amps to 20,000 amps. The fit shown in Figure 3-18b requires only a 4 nT offset and has a $\chi$ value of 1.5.

It should be mentioned that particular emphasis was placed on fitting the data from altitudes greater than 160 km. This range is shown by dashed lines in Figures 3-17b and 3-18b. Data from above this altitude are less sensitive to small scale variations in the current pattern. Also, the spherical harmonic expansions of the geomagnetic field are more accurate at higher altitudes. Looking at only the data between the dashed lines, it is apparent that Model 2 gives the best fit, particularly at 0816:00 and 0820:40.

In order to simulate this model a time dependent neutral wind was combined with the radar-derived conductivities and rocket-measured electric fields. The currents shown by the x's in Figure 3-18a were calculated in this manner. The values plotted for each flux tube were computed at the time the payload passed through the flux tube. The Model 2 currents are plotted in a similar manner as the histogram in the figure for comparison. The time variation of $U_{\text{west}}$ is given at the top of the plot and was determined by requiring the currents derived by the two methods to agree. Model 2 represents the desired self consistent current model. It not only reproduces the magnetometer data, but also agrees with currents computed from Equation 3-12 provided a time dependent neutral wind
29.007 ELECTROJET MODEL 2
9600-17000 AMPS EAST
0 -20000 AMPS WEST
U WEST = .210 x T + 33 (m/s)
U SOUTH = .075 x T + 46 (m/s)
V DRIFT = 200m/s SOUTHERLY (T>300s)

MODEL
x J = \dot{E} + UXB

J EAST (A/M)

HORIZONTAL DISTANCE (KM)

Figure 3-18a

DATA (10 SPIN AVE)
- MODEL
OFFSET = 4.4T
CHI = 1.1T

ΔB (GAMMAS)

MINUTES PAST 0800 UT

Figure 3-18b
is added. Again, there is no proof that this is the only current configuration which is consistent with all the data. However, in the manner of Section 3.4, the following additional trends come out of the modeling attempts.

1. A model in which the westward electrojet is small at the beginning of the flight and grows during the flight produces a better fit to the data. It also requires smaller integrated currents, for example, 17,000 amps maximum for the eastward electrojet, 20,000 amps maximum for the westward electrojet.

2. Since neither the electric field nor the conductivity showed substantial variations during the flight, the neutral wind is the only quantity in Equation 3-10 that could have changed. A change in the westward component of the wind from 50 m/s to 130 m/s over the flight is required to reproduce the current variations.

At first glance it would seem that a time varying neutral wind would violate the relation given by Equation 3-2. However, this relation should only be considered a very crude approximation and might not apply to the entire flight. Also, there is an undetermined southward component of the neutral wind in this equation. In fact, the coefficients \( k_1 \) and \( k_2 \) are such that a small southward wind contributes a large amount to the left side of
Equation 3-2. A southward wind which starts out at about 40 m/s and decreased during the flight to 10 m/s would compensate for the time dependent westward neutral wind, thus maintaining the relation give by Equation 3-2. The variation in $U_{\text{south}}$ used in Figure 3-18a is indicated in the top of the figure.

The increasing westward wind and decreasing southward wind may seem a bit arbitrary. In defense of this model, Figure 3-19 shows the neutral winds measured before and after the flight by the radar in the 3-position mode. The variations in neutral winds assumed by the model are shown as isolated line segments in Figure 3-19. The pre-flight measurements clearly show a decreasing southward component and increasing westward component. It should be pointed out, however, that the variation in Westward neutral wind velocity required by the model is much greater than the gradual trends seen before the flight. There are some rapid changes in neutral wind speed before the flight which are comparable to these, but the 3-position mode measurements are not reliable enough to attach any significance to such changes.

An additional check on the model is provided by the ground-based magnetometer data. The only significant deflections apparent in the ground-based magnetometer data are in the H components at Poker Flat and Fort Yukon. At Poker Flat there was a 17 nT increase in H during the
first half of the flight. At Fort Yukon there was no change in the first half of the flight but a 17 nT decrease in the second half. Model 2 predicts variations over the flight of -30 nT at Poker Flat and -75 nT at Fort Yukon. These numbers include corrections for the effects of ground currents by adding 50% to the calculated perturbations. The difference between these changes and those actually recorded by the ground magnetometers can only be explained by current variations in regions outside the trajectory. For example, an increasing eastward electrojet south of Poker Flat would probably bring the data and model into better agreement. Since the Fort Yukon and Poker Flat magnetometers showed opposite H deflections during the flight, it is quite possible that significant current flow existed outside the 200 km region between the two stations.

The energy dissipated per cm² column in the ionosphere was computed according to Equation 3-14 with $\dot{U}_x = 0$, and with $U_x = -115$ m/s. The resulting profiles are shown by the solid lines in Figure 3-20. Since $Q_J$ is proportional to $E^2$ it is apparent that the Joule heating will be maximum where $\dot{E}$ is maximum. This occurs within flux tubes 7 and 8 just south of the arc. The maximum Joule heating was 9 ergs/cm²-s as opposed to 1 erg/cm²-sec within the arc. This can also be compared with the maximum energy input by precipitating particles which occurs within the arc.
and amounts to 20 ergs/cm²-sec.

Finally, we compute $j_{||}$ according to Equation 3-19. A plot of $J_y$ as a function of horizontal distance is shown in the upper half of Figure 3-21. Equation 3-19 implies that field aligned currents flow in regions where there are gradients in $J_y$. South of 160 km there is some indication of downward field aligned current (i.e., $J_y$ is increasing northward). This current is approximately $0.5 \times 10^{-6}$ A/m². There is a somewhat larger downward field aligned current between 165 and 190 km. The gradient here indicates a downward current of $6 \times 10^{-6}$ A/m². The intense upward current after 190 km is associated with the northern edge of the arc along which the northward current suddenly decreases as a result of the low conductivities poleward of the arc. The upward current here is about $8 \times 10^{-5}$ A/m². Note that when a westward neutral wind of 115 m/s is added all these currents are diminished. Also, the dip in both profiles at a horizontal distance of 130 km may not be real. Spatial gradients in $\vec{E}$ are very large in this region and it is difficult to measure the real conductivity owing to the poor spatial resolution of the radar. Because of this uncertainty it is perhaps more accurate to speak of an average downward field aligned current of $10^{-6}$ A/m² between 30 km and 190 km. This yields a total current of 0.16 amp/m flowing downward. North of the arc there is a current of 0.2 amp/m flowing
Figure 3-21
upward. The field aligned currents computed from Equation 3-19 are indicated by a dashed line in the lower half of Figure 3-21. The parallel currents measured by the magnetometer are indicated by a solid line. Note that the magnetometer detected much larger currents equatorward of the arc. Also, the currents determined by the two methods are exactly opposite in a large part of the ionosphere. This discrepancy will be discussed in Section 4.2.d.
CHAPTER 4
Discussion

4.1 Relation of the Arc to the Outer Magnetosphere.

There is substantial evidence in the particle, electric field, and magnetometer data that the payload traversed four distinct regions of auroral precipitation. Comparison of the data with observations made previously by satellites indicates that it is quite possible that the rocket trajectory spanned a significant portion of the auroral oval.

Figure 4-1 shows the electric fields, net energy flux carried by electrons, and east-west magnetic perturbations measured by the rocket as a function of horizontal distance north of Poker Flat. From 40 to 100 km north there was fairly uniform energy flux. When compared with all-sky camera photos this region is seen to correspond to the diffuse aurora which extended well past the zenith at Poker Flat. The magnetometer trace indicates uniform downward field aligned current flowing in the diffuse aurora.

North of the diffuse aurora was a region of depressed energy flux within which the northward electric field maximized. The field aligned current was upward throughout this region which appeared visually as a dark band separating the discrete arc from the diffuse aurora.

The arc is well delineated in Figure 4-1 by sharp
RICE UNIV. FLIGHT 29.007
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Figure 4-1
gradients in the energy flux and electric field. The northward electric field was zero within the arc. Upward field aligned current flowed from the arc with nearly the same intensity as it did in the dark region to the south.

The northern edge of the arc coincided with the transition from upward to downward field aligned current flow. The low energy flux and small electric field north of the arc suggests possible entry of the payload into the polar cap.

The large scale field aligned current flow pattern in the auroral zone was mapped out by Zmuda and Armstrong (1974). They found that in the evening sector field aligned current flow is downward on the low latitude side of the auroral oval and upward on the high latitude side. The current directions are reversed in the morning sector. Subsequently, Armstrong et al., (1975) used simultaneous ground magnetometer and Triad satellite data to determine the relationship between field aligned currents and the visible aurora. They found that a discrete arc often marks the boundary between eastward and westward electrojets. Also, they showed that the northern edge of the field aligned current region coincides with the poleward boundary of auroral luminosity.

Tsunoda et al., (1976) used simultaneous measurements of radar aurora and Triad satellite data to show that the
region of downward field aligned current flow coincided with the region of diffuse radar emission. Diffuse radar echoes are produced by backscatter from horizontal irregularities in the E-region. These reflections have been associated with the diffuse visual auroral (Tsunoda et al., 1974). Thus, their observations suggest that the transition from downward to upward field aligned current occurs at the poleward edge of the diffuse aurora.

In a more extensive study involving ground-based magnetometer data, Triad satellite data and DMSP auroral imaging data, Kamide and Rostoker (1977) found that the eastward electrojet flows in a region within and north of the diffuse aurora. The diffuse aurora was found to be the site of downward parallel current while the region to the north, which included discrete arcs, was penetrated by upward current. In addition, the arcs were found to be immersed in a region of westward electrojet flow with upward current flowing in the equatorward portion and downward current in the poleward portion.

The similarity of these observations to the results discussed above for the present flight is unmistakable. The one drawback to this comparison is the limited extent of the field aligned current region found here. Zmuda and Armstrong (1974) surveyed the upper and lower latitude boundaries of the field aligned current region, Seldom did the northern boundary lie below 70° magnetic latitude.
Since in the present flight this boundary occurred near Fort Yukon, its magnetic latitude was about 67°. If the upward current region seen here is the same as the large scale current measured by satellite, it must be concluded that the flight occurred during a time when the auroral oval was expanded greatly from its normal position. The results of a survey of the location of aurora as determined by all-sky camera photos from a meridian chain of stations were presented by Snyder and Akasofu (1972). They found that 60-120 minutes before the expansion phase of a substorm, auroral arcs drifted equatorward accompanied by a clearing of the poleward sky. They associated this motion with the thinning of the auroral oval during the growth phase of a substorm. Since a small substorm occurred at 0915 UT, an hour after the flight, the possibility that the oval was in an expanded state is not ruled out.

Once this view is accepted, it becomes possible to relate the boundaries observed here to features in the outer magnetosphere. Winningham et al. (1975), studying ISIS 1 and 2 electron spectrometer data for altitudes of about 1000 km, distinguished two types of precipitation in the high latitude ionosphere. Low energy electrons with no monoenergetic peaks in the spectra were associated with diffuse auroral precipitation. Poleward of this was a region of more energetic electrons whose spectra contained monoenergetic peaks at energies of several keV. These
electrons were presumed to give rise to the discrete aurora. Also, within these regions inverted V events were seen to occur. Inverted V's are characterized by a rise and fall of the energy at which the peak electron flux occurs as a satellite moves meridionally through the auroral zone (Frank and Ackerson, 1971). The lower energy electrons which cause the diffuse aurora were found to have characteristics similar to electrons in the inner regions of the plasma sheet. Winningham et al. called this region the central plasma sheet, or CPS. The electrons with spectral peaks were connected to the outer layers of the plasma sheet and were designated as boundary plasma sheet or BPS precipitation.

In a subsequent study by Winningham et al. (1979) in which ISIS data was combined with ground-based magnetometer data, the relationship of BPS and CPS precipitation to the auroral electrojets was examined. They found that the BPS/CPS boundary lies in the poleward half or at the poleward edge of the eastward electrojet. The BPS, therefore, may encompass the northern part of the eastward electrojet as well as the entire westward electrojet. A more careful examination of ground-based magnetometer data also indicated that the region of upward field aligned current flow coincided with the BPS precipitation zone. Comparing the present results to those described above leads to the conclusion that the transition from downward
to upward field aligned current, which in this flight occurred at the northern edge of the diffuse aurora, may correspond to the BPS/CPS boundary when mapped out into the magnetosphere. Since the arc was immersed in a large scale upward current, it can then be associated with BPS precipitation.

The relationship of this aurora with the outer parts of the magnetosphere can be made more complete by examining the results of Sugiura (1975) who analyzed magnetic data taken by OGO 5 at distances of from 4 to 10 $R_E$ in the magnetotail. He showed that a layer of field aligned current flows along the boundary of the plasma sheet far back into the tail. Since the directions of these currents corresponded to the direction of the poleward set of field aligned currents as mapped out by the lower altitude Triad data (subsequently designated the "region 1" field aligned currents by Iijima and Potemra (1976)), Sugiura identified these as one and the same currents. He thus concluded that auroral arcs, which exist at the high latitude side of the auroral oval, must be on field lines which flow along the boundary of the plasma sheet. He also showed how a generator in the distant tail could drive both the equatorward and poleward field aligned currents and give rise to the observed ionospheric electric fields.

The trapping boundary is another magnetospheric boundary which may be identified for this arc. Ackerson and Frank
(1972) defined the trapping boundary as the position at which the flux of electrons with energies greater than 45 kev drops off sharply. This boundary would then correspond to the outer limit of the region of trapped radiation and might separate closed magnetic field lines from field lines which attach to the interplanetary magnetic field. Due to the low altitude of the rocket, no significant fluxes of electrons with E > 45 kev were detected throughout the flight. However, we can still specify the location of the trapping boundary by taking advantage of previous satellite results. Romick and Sharp (1967) used photometer data with satellite particle data and found that auroral arcs occurred poleward of the trapping boundary while diffuse aurora occurred equatorward of it. With this information we may conclude that the trapping boundary must lie somewhere in the dark region between the diffuse aurora and the discrete arc. The boundary can be located more precisely by considering the results of Gurnett and Frank (1977) who found the trapping boundary to be equatorward of an extended region of broadband electrostatic noise. Figure 4-2 shows the broadband noise as a function of flight time detected by the spherical probes for the present flight. The rise in intensity of the noise occurs just north of the diffuse aurora. Thus, the transition from downward to upward field aligned current is probably
also the trapping boundary.

It was mentioned earlier that the inverted V events usually occur in the region of BPS precipitation. This suggests the possibility that the arc studied here might have been the low altitude signature of an inverted V event. Examination of the electron spectrometer data shows that the monoenergetic peaks in the spectra increased in two distinct steps from 1 kev at the edges of the arc to 6 kev at the center. This is different from the gradual rise in peak energy seen in the satellite data. However, the arc studied here possessed other features in common with inverted V events. These features are summarized below.

(1) Lin and Hoffman (1979) did a statistical study of inverted V characteristics. They found the average width of an inverted V to be about \(0.5^\circ\) of latitude, although in the midnight and evening sectors the average widths were somewhat greater. The 50 km extent of the precipitation region for the present flight corresponds to a latitudinal width of about \(0.5^\circ\).

(2) Armstrong et al. (1975) found that inverted V's occur primarily in the region of upward field aligned current flow. Also, Kisabeth and Rostoker (1979) associated inverted V's with the region of precipitation referred to above as the boundary plasma sheet. They also found that arcs located in the poleward region of the
auroral oval were associated with inverted V events.

(3) Gurnett and Frank (1977) studied the location of broadband electrostatic noise detected by the Hawkeye 1 and IMP 6 satellites. They found that broadband noise was associated with inverted V's and was probably a result of the acceleration of auroral electrons in parallel electric fields. The broadband noise observed here and shown in Figure 4-2 coincided not only with the region of auroral precipitation, but also existed to a significant extent in the dark region equatorward of the arc. The uniformity of the broadband noise and the upward field aligned current observed for the present flight suggests a connection between these two regions. This will be discussed further in Section 4.2.c.

(4) Gurnett (1971) has reviewed the electric field structure in inverted V events. Sometimes inverted V's are associated with spike-like electric fields pointing inward toward the center of the structure. He suggested that such fields were the low altitude projections of V-shaped electrostatic potential regions located above the ionosphere. More recently Burch et al. (1976) noted that inverted V's were observed with this field pattern only about 5% of the time. Another electric field pattern often seen by them was a simple decrease in convection electric field toward the center of the inverted V. This pattern is similar to that observed for the present flight.
Note that if the precipitation region in this arc was extended equatorward, and if the enhanced conductivity caused by this precipitation shorted out the electric field within, then the remaining electric field might appear spike-like. This would be especially true if the potential drop between, for example, the poleward edge of the diffuse aurora and the arc was held constant. Then as the region of non-zero electric field became narrow the northward field would become more intense. The lack of an oppositely directed spike at the poleward boundary of the inverted V may be a result of the small potential difference between the auroral zone and the polar cap. The appearance of multiple reversals in the electric field within inverted V's is also common, but such behavior is difficult to explain in terms of any simple model.

The electric field data and electron spectrometer data can be combined in such a way as to reconstruct the equipotential contours above the auroral arc (Vondrak, private communication). This can be done by assuming that the monoenergetic peaks in the electron spectra give the potential drops along the magnetic field lines through which the particles have been accelerated (Evans, 1974). Since $\int E \cdot dl = 0$, by taking the line integral of $\mathbf{E}$ around closed loops aligned along $\mathbf{B}$, the potential above the acceleration region can be computed and equipotential
contours drawn. Figure 4-3 shows the results of this calculation for the present flight. $\phi_\parallel$ is the ionospheric potential distribution computed from the rocket-measured northward electric field. The potential is assumed to be zero at the equatorward edge of the arc. The field aligned potential drop $V_\parallel$ was determined from the measured differential energy spectra for electrons with pitch angles between 0 and 5 degrees. The resulting potential distribution in the magnetosphere above the acceleration region is given by $\phi_m$. Note that the step-like changes in $V_\parallel$ imply large spatial gradients in $\phi_m$ or spike-like electric fields in the magnetosphere. Such fields have been observed by Mozer (1980) and are believed to be the signatures of electrostatic shocks along field lines connected to inverted V precipitation regions. The exact configuration of these shocks is more complicated, however, because the potential drop $V_\parallel$ is a function of pitch angle. For electrons in the pitch angle range 60° to 65° $V_\parallel$ increases to its maximum value at the center of the arc in one step rather than the two step rise shown in Figure 4-3. In either case the equipotential contours show that the ionosphere is very effectively decoupled from the magnetosphere. This potential configuration is similar to that proposed by Gurnett (1971) and Burch et al. (1976).
(5) Sharp et al. (1979) detected upward moving ions within inverted V's using instruments aboard the S3-3 satellite at 8000 km altitude. The upward moving ions may result from the upward directed parallel electric field associated with the V-shaped electrostatic potential regions. As discussed in Section 3.5, the simultaneous radar and rocket electric field measurements for this flight indicated the presence of upward moving ions at 100 m/s within the auroral arc.

(6) Lin and Hoffman (1979) also found in their statistical survey that the edges of inverted V's were associated with field aligned electron precipitation. Pitch angle distributions of the electrons observed in the present flight have been analyzed by Pulliam et al. (1980). They showed that although electrons with energies above a kev were isotropic over the entire flight, the lower energy electrons exhibited substantial field alignment at both edges of the arc, as well as in two isolated events at the center of the arc.

(7) Lin and Hoffman (1979), studying electron energy spectra in inverted V events, fitted a Maxwellian distribution to that part of the spectra above the energy peak. According to Evans model (Evans, 1974) this specifies the temperature and density of auroral electrons before their acceleration through a field aligned potential drop. The electron densities and temperatures that Lin and Hoffman
found were characteristic of the plasma sheet. A similar analysis performed by Pulliam et al. (1980) for the arc studied here also yielded temperatures and densities typical of the plasma sheet.

(8) Ackerson and Frank (1972) found that most inverted V events occurred at or poleward of the 45 kev trapping boundary. As discussed earlier, the trapping boundary for this arc was probably coincident with the field aligned current reversal located at the poleward edge of the diffuse aurora.

Taken together the above results are convincing evidence that the arc studied in this experiment was the ionospheric signature of an inverted V precipitation event. The response of the ionosphere to this precipitation will be discussed in the following sections.

4.2 Ionospheric Response.

4.2.a Horizontal Current Flow. Auroral electrojets have been measured previously by several Rice University sounding rockets. Table 4.1 summarizes the magnetometer results of these flights and the present flight. The second column in the table gives the deflection in the H component of the local ground magnetogram at the time of flight. The third column gives the electrojet current magnitudes implied by the ground magnetic perturbations. These are computed by assuming the currents flow in a filament at an altitude of 120 km above the station,
<table>
<thead>
<tr>
<th>FLIGHT</th>
<th>H(nT)</th>
<th>Electrojet (Amps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.321 (Cloutier et al., 1970)</td>
<td>- 50 (CHU)</td>
<td>Ground 20000 West Rocket 4000 West</td>
</tr>
<tr>
<td>18.110 (Cloutier et al., 1973)</td>
<td>+ 80 (FYU)</td>
<td>32000 East 5000 East</td>
</tr>
<tr>
<td>18.111 (Sesiano &amp; Cloutier, 1976)</td>
<td>- 52 (FYU)</td>
<td>21000 West 2000 East 2000 East 1100 West</td>
</tr>
<tr>
<td>18.112 (Casserly &amp; Cloutier, 1975)</td>
<td>+140 (FYU)</td>
<td>56000 East 3000 East 4000 East</td>
</tr>
<tr>
<td>29.007 (This Experiment)</td>
<td>+ 80 (FF)</td>
<td>32000 East 17000 East</td>
</tr>
<tr>
<td></td>
<td>- 80 (FYU)</td>
<td>32000 West 20000 West</td>
</tr>
</tbody>
</table>

**TABLE 4.1**
It has also been assumed that one-third of the ground disturbances are caused by induced currents flowing within the earth. The last column in Table 4.1 gives the electrojets inferred from the rocket-borne magnetometer data. In all the previous flights the rocket-measured current is much less than that computed from the ground perturbations. This discrepancy was usually attributed to the presence of a large scale electrojet which adds a constant offset to the rocket-borne magnetometer data. These offsets are ignored in the modeling procedure because they may also be produced by errors in the reference field or errors in precalibration of the magnetometer bias field. There are two reasons to believe that this difficulty does not exist for the present experiment. First, at an altitude of 300 km the magnetometer for 29.007 measured a field magnitude equal to that given by the reference field to within 1 nT. This is to be expected if all the currents flow below 150 km altitude. In the previous flights the magnetometer measurements were always more than 20 nT offset from the reference field. Since the apogee altitudes for the previous flights were usually less than 250 km, it is conceivable that the magnetometers were always measuring some contribution from large scale electrojets.

A second argument for discounting the possibility of a large scale current for the present flight is pro-
vided by the simultaneous electric field and conductivity measurements. As discussed in Section 3.6, the magnetometer-derived currents were greater than those determined from Equation A.12. Thus, it is doubtful that any part of the current was neglected in the modeling.

The 10000 amp differences between the rocket and ground-based measurements for this flight are probably due to the difficulty in determining a base line from which to measure perturbations in the ground magnetogram. Also, there may have been some contribution to the H component on the ground from currents flowing outside the region spanned by the trajectory.

4.2.b Neutral Winds. Perhaps the most interesting aspect of the electrojet current pattern for this experiment was the role played by the neutral wind. Although electric fields are usually diminished within premidnight auroral forms, the current in these high conductivity regions can be substantial owing to the neutral wind.

The westward wind implied by the data in this experiment is consistent with theoretical predictions of atmospheric motion in the premidnight sector of the auroral zone. Fedder and Banks (1972) modeled polar cap neutral winds including the effects of viscosity and ion drag. The ions are driven antisunward over the polar cap by a large scale dawn-to-dusk electric field. The time scale for acceleration of the neutral gas by ion drag is on the
order of hours. If the large scale electric field is turned off suddenly, the inertia of the neutrals maintains the antisunward flow. Thus, Fedder and Banks predicted mostly southward neutral winds near midnight in the auroral zone. Before and after midnight the flow is diverted toward the east and the west forming a two cell convection pattern with closure along the auroral zone.

Heaps and Megill (1974) made similar calculations only applied them to the auroral zone rather than to the polar cap. They used as input the observed pattern of northward electric fields before midnight and southward electric fields after midnight and found that westward winds in the late evening sector were predominant with only small meridional components. Both Fedder and Banks and Heaps and Megill found neutral wind velocities which increased with altitude.

Early measurements of neutral winds were made by barium releases, satellite drag analyses and interferometry. None of these methods has the spatial and temporal resolution required to compare with the results of the present experiment. Brekke et al. surveyed auroral zone neutral winds using Chatanika radar in the three position mode. Although they were able to confirm the two cell convection pattern predicted by Fedder and Banks, their data in the premidnight sector were confusing.

A subsequent survey by Nagy et al. (1974), again
using Chatanika radar, supported the notion of westward winds being dominant before midnight. Recently Hays et al. (1979) compared a theoretical model for thermospheric winds at high latitude with this latter survey. They concluded that their model could be made consistent with the observations by including a pressure gradient force sustained by enhanced Joule heating at midnight.

Bering and Mozer (1975) measured very large (300 m/s) westward neutral winds during a rocket flight into a premidnight aurora. Their method was somewhat indirect, involving a comparison of conductivities computed in two different ways, but the dominance of westward motion is significant.

The above theories and experiments support the present observation of westward wind flow before midnight. It should be emphasized, though, that the dynamic nature of the ionosphere in this time sector makes any generalizations unjustified.

Evidence for a time varying neutral wind was presented in Section 3.6. For this there is much less observational support. As an example of the difficulty in detecting such rapid time variations, Chatanika radar requires 15 minutes to get one reliable, independent neutral wind measurement. Barium releases are probably the most promising indicators of rapid changes of wind magnitude. However, the nature of these experiments makes it difficult to separate temporal
and spatial effects.

One interesting aspect of the change in neutral wind speed is its possible connection with a change in arc brightness. As mentioned in Section 3.1 the arc studied here brightened substantially during the first half of the flight. This coincidence in time suggests a possible relation between the brightening of the arc and the enhanced westward neutral wind. Several investigators have discussed possible effects of neutral wind flow on ionosphere-magnetosphere coupling. Coroniti and Kennel (1972) suggested that neutral winds can affect convection in the outer magnetosphere because ion drag tends to make the neutrals move at the ion velocity. As \( \mathbf{U} \) approaches \( \mathbf{v}_i \) the effective collision frequency in the ionosphere is reduced so that there is less resistance to the motion of field lines through the ionosphere. It is not clear, however, how this might affect the generation of aurora.

Sato (1975) discussed how a neutral wind blowing along an electrojet might change the flow of current around an arc, inducing field aligned currents and initiating the growth of instabilities which can support parallel electric fields.

Evans et al, (1977) observed an arc with an electric field structure similar to that found here. They suggested that a westward wind could act as a dynamo, i.e., move charge against the ambient field. It should be mentioned,
however, that the neutral wind dynamo mechanism can only be applied to either quiet time arcs or perhaps to variations in the intensity of brighter aurora. The amount of energy released during substorms undoubtedly requires an energy source in the magnetosphere rather than the ionosphere.

4.2.c Joule Heating. Before discussing Joule heating, more should be said about the observed anticorrelation between the northward electric field and the net energy flux carried by the particles. Evans et al. (1977) observed a similar anticorrelation in an auroral rocket flight. They proposed two possible explanations. If the magnetospheric generator which drives the large scale ionospheric currents is a constant current source then by Ohm's law the potential drop between two points in the ionosphere is inversely proportional to the conductivity. Since regions of enhanced particle influx have higher conductivities than the surrounding plasma, the electric field is expected to be reduced. On the other hand, the same relation might apply even if the magnetosphere is a constant voltage source provided there is a large resistance somewhere else in the circuit. Evans et al. favored the second explanation and suggested that the large resistance occurred along field lines connected to the arc. In this region of high resistance parallel electric fields exist that accelerate auroral electrons.
The shorting of the electric field in an enhanced conductivity region can be prevented if the Hall current driven by the east-west electric field is strong enough and of the right sign. In the present flight the westward electric field drives a northward Hall current, thus reinforcing the polarization effects. De la Beaujardiere et al. (1977) have shown that for morning sector arcs the electric field is not shorted out. This is because the meridional component of the electric field is southward, while the zonal component is westward. The Hall current driven by the westward electric field opposes the polarization produced by the Pedersen current driven by the southward electric field.

In terms of energy dissipation the high electric field observed adjacent to arcs implies enhanced Joule heating in these regions. Evans et al. (1977) computed a profile of Joule heat input for their flight and compared it to a profile of net energy influx due to precipitating particles. They found that at the edge of the arc the Joule heat input drops off sharply where the particle flux increases. Summing the two, they found that the energy input to the ionosphere was fairly constant across the arc boundary. They suggested that the high Joule heating region and the arc were actually one extended region of energy dissipation. That is, energy can be dissipated in the ionosphere by either Joule heating or particle precipi-
A similar pattern is found for the present flight. However, the connection between these two regions is suggested by two other observations which Evans et al. could not make. First, the field aligned current is uniformly upward in both regions despite large gradients in electric field and particle flux at the equatorward boundary of the arc. Second, within both regions broadband electric field noise was detected. Although these relations are suggestive, the implications insofar as auroral acceleration is concerned are somewhat obscure. However, the variable neutral wind speed and the brightening of the arc imply a possible connection. As shown in Figure 3-20, the effect of the neutral wind is to reduce the Joule heating rate wherever the electric field is northward. Thus, the onset of the wind represents a net reduction in the amount of energy dissipated in the ionosphere. If the total energy dissipation rate in the ionosphere must remain constant, the circuit might compensate by increasing the energy and flux of the precipitating particles. Better neutral wind measurement techniques could enable testing this idea simply by trying to correlate brightness variations in visible aurora with sudden changes in wind direction and magnitude.

4.2.d Field Aligned Currents. As mentioned in Section 3.4, there is a serious discrepancy between the
field aligned current flow measured by the magnetometer and that computed by taking the one dimensional divergence of the horizontal currents. Before discussing this discrepancy it may be helpful to examine some of the previous measurements of field aligned currents associated with auroral arcs. The Rice University group has made several high resolution measurements of field aligned currents in auroral arcs (Cloutier et al., 1970; Cloutier et al., 1973; Casserly and Cloutier, 1975; Sesiano and Cloutier, 1976). Although the results differ there are some unifying features. All showed an upward field aligned current roughly coincident with the auroral arc. Although precipitating electrons constitute an upward current, the net current carried by the energetic electrons was usually less than half the current measured by the magnetometer. In addition, the previous Rice experiments found a downward current of equal magnitude displaced to the north or south of the upward current.

The field aligned current for the present experiment is slightly different in that the arc was embedded within an upward current region with no significant variation associated with the equatorward arc boundary. In comparing magnetometer results of this flight to those of previous Rice flights, it is important to note that the data reduction technique differed somewhat. The present flight benefited by having a very accurate, independent measurement
of the payload spin frequency provided by the star sensor. In the absence of such independent attitude information, the spin frequency for previous flights was determined by fitting a polynomial to the magnetometer data. Such a procedure not only conceals large scale field aligned currents, but also can cause distortions in the derived parallel current structure (Robinson, 1979). However, these distortions are probably insignificant when the parallel currents are very large (> $10^{-5}$ A/m²). Also, the polar angle $\theta_c$ can sometimes be used to determine the presence of such distortions.

By itself the lack of an upward current variation at the equatorward arc boundary is not a major difficulty. It may well be that the electric field and conductivity change in such a way as to keep $J_y$ constant across the boundary. It is much more difficult to explain the lack of agreement between the magnetometer-measured currents and those computed from the divergence of the horizontal current.

Previous attempts at comparing field aligned currents computed from horizontal gradients and from magnetometers have been made. Kamide and Horwitz (1978) and Vondrak et al. (1979) used simultaneous Chatanika radar current measurements and Triad magnetometer data and found good agreement between field aligned currents computed by the two methods.
The observations of Tsunoda et al. (1976) are more similar to those of the present flight. As discussed in Section 4.1, they used simultaneous radar aurora and satellite field aligned current data to locate the transition from downward to upward current flow. In one case, a simultaneous electric field measurement was made by chemical release. At the location of the transition no substantial gradient in the electric field was observed, Tsunoda et al. concluded that field aligned currents are not produced by horizontal gradients in ionospheric conductivity or electric field, but are controlled by large scale processes in the magnetospheric tail.

One possible explanation for the discrepancy in field aligned currents computed by the two methods for the present flight is current closure above 160 km. The parallel currents computed from Equation 3-19 presumably flow from the top of the ionospheric current layer at 160 km altitude. The payload, however, was well above this altitude throughout much of the flight. If there is some closure of currents above 160 km the field aligned currents measured at two different altitudes will be unequal. Although possible, this current closure is extremely unlikely. The low collision frequencies above 160 km make it very difficult for current to flow perpendicular to the magnetic field.

Discounting this possibility there remains only one
way to satisfy current continuity in a stationary state situation. Equation 3-19 contains the assumption 
$\partial j_x/\partial x = 0$. Kisabeth and Rostoker (1979) pointed out that in the region of the Harang discontinuity there may be considerable divergence of the westward and eastward electrojets up the field lines. Thus the eastward current weakens to the east and the westward current weakens to the west. The probability of the arc in this experiment being associated with the Harang discontinuity was discussed in Section 3.1. If so, for this particular arc it is not sufficient to compute field aligned currents by taking a one dimensional divergence of the current.

Figure 4-4 is a sketch of how current might flow in an arc associated with the Harang discontinuity. Recall that the arc in this experiment was rotated 15 to 20 degrees clockwise from magnetic East-West alignment, in agreement with the orientation of the Harang discontinuity. Although this model may account for the discrepancies found in this experiment, the need for further measurements of Harang discontinuity arcs is clearly indicated.

The discussion above was primarily concerned with the field aligned currents south of the arc. The northward current shown in Figure 3-18 indicates a strong upward field aligned current in the northern part of the arc that is not apparent in the magnetometer data. However, the thickness of this current sheet cannot be determined since the
radar data gives conductivities with a spatial resolution of about 20 km. On the all-sky camera photos the northern edge of the arc appeared very sharp, so that it is possible this arc-related field aligned current flowed in a very thin sheet. Examination of the magnetometer data for each spin shows spike-like features lasting for about 2 seconds at the poleward boundary of the arc. These were also correlated with electric field fluctuations. Examination of the data for the rest of the flight revealed a similar feature at 0820:55 where there was another sharp gradient in energy flux. These electric and magnetic fluctuations may be the manifestations of plasma instabilities driven by intense field aligned currents at the poleward edge of the arc. The duration of these spikes implies a region of disturbance approximately 1 km wide.

The arc-related current discussed above flows in addition to the less intense field aligned current flowing upward from within the arc. It was mentioned in Section 3.5 that the precipitating energetic electrons and the upward moving ions could account for all the upward current measured by the magnetometer within the arc. On the other hand, south of the arc, where the current is also upward at 4 μA/m², there are neither significant fluxes of electrons, nor upward drifting ions. The current in this region must therefore be carried by downward moving thermal
electrons. This is in agreement with the ideas of Kamide and Rostoker (1977), who discussed the problem of current carriers in some detail. For the present flight, however, it is surprising that two adjacent regions have equal field aligned current flow even though the current carriers are completely different.

4.2.e F-region Hole. There are three possible explanations for the appearance of the electron density hole at 200 km altitude equatorward of the arc. Hays et al. (1973) have suggested a mechanism by which the recombination rate is increased in regions where molecular nitrogen is present. The $N_2$ reacts with $O^+$ producing $NO^+$ which is neutralized by dissociative recombination. The rate coefficient for this reaction is larger than the recombination rate with only $O^+$ present. Although the concentration of $N_2$ at 200 km is normally very small, the F-region hole occurs on field lines along which the Joule heating is maximum. Bates (1974) has argued that Joule heating can cause an upward flow of neutral molecules along magnetic field lines in the auroral ionosphere. Although the coincidence of the hole with the region of maximum Joule heating supports this explanation, the actual heat input of 9 ergs/cm²-sec seems too small to produce the required effect.

Another mechanism for changing the recombination rate was suggested by Banks et al. (1974). The production
rate of \( \text{NO}^+ \) from \( \text{O}^+ \) and \( \text{N}_2^+ \) is increased considerably in the presence of large perpendicular electric fields. Once formed the \( \text{NO}^+ \) recombines quickly producing a localized depletion in electron density. However, the 40 mV/m electric field found here south of the arc does not seem large enough to affect the rate coefficient significantly (Banks et al., 1974).

Perhaps the most likely explanation for the F-region hole is that it represents a real decrease in ionization rate owing to the low flux of precipitating electrons. The electron spectrometer data showed that the spectra of electrons in this region had high energy tails which could be fit to a Maxwellian distribution. The density of the source plasma was typically 0.03 to 0.07 cm\(^{-3}\). This can be compared with source densities of 0.5 to 1.0 cm\(^{-3}\) for electrons within the arc. Thus, the dark band and F-region hole may be manifestations of a localized depletion in the plasma sheet electron density. The large northward electric field along these flux tubes is caused by the absence of charge carriers, which normally drift to reduce the ambient field.
CHAPTER 5  
Summary and Conclusions

There is evidence both in the ground magnetometer data and in the rocket data that the auroral arc studied here was associated with the Harang discontinuity and occurred during the growth phase of a substorm. During the growth phase the auroral oval often expands equatorward from its quiet time location (Snyder and Akasofu, 1972). This is consistent with the narrow region of upward field aligned current flow and the low latitude of the polar cap boundary found in this experiment. The upward field aligned current detected by the magnetometer was the entire Region 1 Birkeland current as defined by Iijima and Potemra (1976). The relation of the field aligned currents to the diffuse and discrete aurora was compared with that typically inferred from satellite data. This comparison enabled the visual aurora to be associated with specific regions in the outer magnetosphere.

Figure 5-1 shows the probable configuration of the magnetosphere at the time of the flight. The diffuse aurora was threaded by field lines carrying downward field aligned current and connected to the central plasma sheet. The transition from downward to upward field aligned current at the north edge of the diffuse aurora corresponds to the boundary of stable trapping as defined
by Roederer (1970). Poleward of this boundary was the entire Region 1 Birkeland current which extended over about 1° of invariant latitude or 100 km in the ionosphere. (The ionospheric projection is exaggerated in the figure.) In the equatorward half of this region was a dark band within which the net energy flux carried by precipitating electrons was less than 0.2 ergs/cm²-s. The poleward portion of the upward field aligned current region contained the arc which was characterized by energy fluxes as high as 20 ergs/cm²-s. The entire upward field aligned current region was the site of broadband electric field noise. Field lines from this extended region map to the boundary plasma sheet.

Electron energy spectra taken from within the dark band and from within the arc indicated that the former mapped to a tenuous region of the plasma sheet with electron densities of 0.05 cm⁻³, while the latter mapped to a region with densities of 0.7 cm⁻³.

Poleward of the arc the depressed energy flux, small electric field and absence of significant field aligned current indicated passage of the payload into the polar cap.

The ionospheric response to the auroral precipitation is summarized in Figure 5-2. The upper part of the Figure is an electron density contour plot constructed from the radar data during the middle part of the flight. The
parallel current was determined from the rocket magnetometer data. The upward current of 4 µA/m² within the arc was carried by precipitating electrons and upward drifting ions. For the east-west currents, the magnetometer, radar and double probe results were combined to construct a self consistent model. The model required a westward neutral wind which increased from 35 m/s to 115 m/s during the flight. This time dependent neutral wind may have been associated with the brightening of the arc during the flight. The east-west current intensities shown in Figure 5-2 are those that existed in the particular flux tube at the time the payload passed through it. The northward current increased gradually to a maximum within the arc then dropped off sharply at the northern edge of the arc. The divergence of the northward current does not agree with the field aligned currents measured by the magnetometer. This was attributed to the divergence of the eastward and westward electrojets in the arc.

Figure 5-2 also shows the amount of energy dissipation \( Q_J \) due to Joule heating of the neutral atmosphere. This reached a peak of about 9 ergs/cm²-sec in the high electric field region just to the south of the arc.

The last trace in Figure 5-2 shows the parallel potential drop through which the electrons within the arc fell. This was determined from the peak in the energy spectra for electrons with pitch angles between 0 and 5
degrees. For electrons with larger pitch angles $V$ increased to it's maximum value in one step at the southern edge of the arc, in contrast to the two step rise shown in the Figure. It's subsequent decrease at the northern edge of the arc also occurred in one step.

Some of the results of this experiment may be generally applicable to all auroral arcs. However, in many ways the event studied here was unique and may not be typical of quiet time auroral arcs. For example, the width and location of the Region 1 Birkeland currents found for this aurora does not agree with that observed by satellites in the premidnight sector. Since it has been shown that the relationship between these currents and the visual aurora seems to be very typical, one might conclude that during the expansion of the auroral oval, which may sometimes be associated with the growth phase of a substorm, all magnetospheric and ionospheric boundaries move together. This may explain the abnormally intense Region 1 Birkeland current measured here. The $4 \times 10^{-6}$ A/m$^2$ current, when integrated over the 100 km wide region through which it flowed, gives a total current of $0.4$ A/m. The typical width of the Region 1 current is 400 km. If $0.4$ A/m is spread over a more extended region it would produce a current density more similar to that normally seen.

The appearance of the large F-region hole equatorward of the arc might also be evidence that this aurora was
somewhat atypical. As explained in Section 4.2, this depression in electron density probably resulted from the low density of the source plasma. This low density region in the plasma sheet may be associated with the substorm which occurred about an hour after the flight. On the other hand, such a depletion might be a natural consequence of auroral arc or inverted V formation.

Several arguments have been given supporting the association of the discrete arc with an inverted V precipitation event. However, the step-like rise in peak energy is somewhat unusual. Perhaps the smooth transition in peak energy seen in the satellite data is actually a multitude of small step-like increases. Thus, the two step rise observed here may be an initial stage in the growth of a more well defined inverted V event.

When considering the generality of the results of this experiment one should also consider the field aligned current comparison discussed in Section 4.2,d. Although the arc was uniform in the east-west direction, there seemed to be evidence that a substantial portion of the upward field aligned current was derived from the divergence of the eastward and westward electrojets. It is doubtful, therefore, that these results can be used to support any of the existing theories of arc formation, since they all assume gradients in the east-west direction to be negligible. Kamide (1978) has argued that the
Harang discontinuity need not be associated with upward field aligned current, but that the eastward electrojet is diverted northward across the discontinuity to flow into the westward electrojet. The present results seem to argue against this model since they imply upward divergence at the ends of the electrojet.

The horizontal current profile observed in this experiment is certainly not unique. However, the role played by the neutral wind should be emphasized, since this too is usually left out of auroral arc theories. Rees (1971) showed that the H component in ground magnetograms could be correlated with the east-west neutral wind speed. The time dependent westward neutral wind inferred from the present results suggests that some of the variations in H recorded by ground magnetometers may be associated with rapid changes in the motion of the neutral atmosphere. This is especially true during times when auroral precipitation creates widespread regions of enhanced conductivity.
APPENDIX A

Radar Elevation Scan Measurements of Ionospheric Electric Field

Since the radar measures only one component of the ion motion, three non-collinear measurements are required to determine the vector drift velocity. In the three position mode this is accomplished by fixing the radar elevation angle and making measurements at three different azimuths. Since the three positions may be separated by as much as 100 km in the ionosphere spatial uniformity over these distances must be assumed. In the elevation scan (ELSCAN) technique the problem of poor spatial resolution is circumvented by combining line-of-sight velocity measurements at two difference altitudes with ion mobilities computed from electron density data. In the ELSCAN mode such measurements are used to produce meridional profiles of the ionospheric electric field. This section describes the ELSCAN method and how it was applied for the present experiment.

We begin by reviewing the method by which the components of the ionospheric electric field perpendicular to \( \mathbf{B} \) can be determined from line-of-sight velocities at two different altitudes. A more detailed discussion can be found in Doupnik et al. (1977).

Because the probing pulse transmitted by the radar
is 320 μsec long, the ion velocity measured by the instrument involves an integration over a 96 km long column of the ionosphere. The measured velocity $V_i$ is given approximately by

$$V_i = \frac{\int_{r_1}^{r_2} n_e(r)W(r)v(r)dr/r^2}{\int_{r_1}^{r_2} n_e(r)W(r)dr/r^2} \quad A.1$$

Here $r_1$ and $r_2$ define the limits of the range gate, $n_e$ is the electron density, $v_i$ is the range dependent ion velocity and $W(r)$ is a triangular weighting function that is maximum at the center of the range gate. This weighting function approximates the way in which data is sampled in the radar autocorrelator.

The velocity $\dot{v}(r)$ is given by the steady state ion momentum equation:

$$\dot{v}(r) = \ddot{u}(r) + \frac{\Omega_i}{Bv_i(r)} \dot{v}(r) \times \vec{B} + \frac{\Omega_i \vec{E}}{Bv_i(r)} \quad A.2$$

where $\ddot{u}(r)$ is the neutral wind velocity, $\Omega_i$ is the ion gyrofrequency, and $v_i(r)$ is the ion-neutral collision frequency. Equation A.2 can be manipulated to give $\dot{v}(r)$ explicitly in terms of $\ddot{u}, v_i, \Omega_i, \vec{E}$ and $\vec{B}$. If the component of $\ddot{u}$ parallel to $\vec{B}$ is neglected, this expression is given by
\[ \nu_i = \frac{\Omega_i \nu_i}{\nu_i^2 + \Omega_i^2} \left( \frac{\ddot{E} + \ddot{U} \times \ddot{B}}{B^2} \right) \]

\[ + \frac{\Omega_i^2}{\nu_i^2 + \Omega_i^2} \left( \frac{\dddot{E} \times \dddot{B}}{B^2} \right) + \frac{\nu_i^2 \dddot{U}}{\nu_i^2 + \Omega_i^2} \]

A.3

In order to get something comparable to Equation A.1, we multiply both sides of the above equation by \( W(r)n_e(r)/r^2 \) and integrate from \( r_1 \) to \( r_2 \). To simplify the integration on the right side, we assume \( \dddot{E} \) is independent of \( r \) and that \( \dddot{U}(r) = \dddot{U} = \text{constant within the range gate} \). Then dividing by the normalization factor \( \int_{r_1}^{r_2} W(r)n_e(r)dr/r^2 \) gives

\[ \nu_i = k_1 \left( \frac{\dddot{E} + \dddot{U} \times \dddot{B}}{B} \right) + k_2 \left( \frac{\dddot{E} \times \dddot{B}}{B^2} \right) + (1 - k_2) \dddot{U} \]

A.4

\( k_1 \) and \( k_2 \) are range integrated mobility coefficients given by

\[ k_1 = \frac{\Omega_i \int_{r_1}^{r_2} \frac{\nu_i(r)}{\nu_i^2 + \Omega_i^2} \frac{n_e(r)W(r)dr}{r^2}}{\int_{r_1}^{r_2} W(r)n_e(r)dr} \]

A.5

and
\[ k_2 = \Omega_i^2 \frac{\int_{r_1}^{r_2} \frac{1}{v_i^2 + \Omega_i^2 r^2} n_e(r) W(r) \, dr}{\int_{r_1}^{r_2} n_e(r) W(r) \, dr} \]

In practice, \( k_1 \) and \( k_2 \) are calculated using electron density data obtained between line-of-sight velocity measurements. The pulse length used for measuring \( n_e \) is 60 \( \mu \)sec long so that these data are measured with better spatial resolution than the velocity data. The integration in Equation A.4 is done along the line-of-sight with \( r_1 \) and \( r_2 \) approximately 96 km apart. If the radar look angle is not along the magnetic field, then the assumption that \( \vec{E} \) is independent of \( r \) is invalid. Although the weighting function has the effect of limiting the effective length of the range gate to about 48 km, in the auroral ionosphere there may be large gradients in \( \vec{E} \) which produce indeterminable errors in \( k_1 \) and \( k_2 \). Other uncertainties in these parameters will be discussed below.

Above 140 km \( v_i \ll \Omega_i \) so that if \( r_1 \) and \( r_2 \) are both above this altitude \( k_1 \rightarrow 0 \) and \( k_2 \rightarrow 1 \). Therefore, for
range gates centered above about 160 km

\[ \hat{V}_i = \frac{\vec{E} \times \vec{B}}{B^2} \]  

A.7

For this experiment the radar was pointing in the magnetic meridian toward magnetic north. We adopt an orthogonal coordinate system with the z axis positive upward along \( \hat{Z} \), x positive to the east and y positive to the north. If the elevation angle of the radar is \( \beta \), Figure A-1 shows that the line of sight velocity is given by

\[ V_{LS} = V_y \sin(\beta + I) - V_z \cos(\beta + I) \]  

A.8

In most cases the component of \( \hat{V} \) parallel to \( \hat{Z} \) is small so that

\[ V_{LS} = V_y \sin(\beta + I) \]  

A.9

Measurement of \( V_{LS} \) for a range gate centered above 160 km thus gives the y component of \( \vec{E} \times \vec{B}/B^2 \) from Equation A.7, or, in effect, \( E_x \). For range gates centered in the E-region, the meridional component of ion velocity is, from Equation A.4,
\[ V_y = \frac{k_1 E_y}{B} + k_1 U_x + k_2 \left( \frac{\dot{E} \times \dot{B}}{B} \right)_y + (1 - k_2) U_y \]  

Equation A.10

Let \( V_1 \) and \( V_2 \) be the measured meridional components of the ion drift for the E-region and F-region, respectively. Then from Equation A.10 the \( y \) component of \( \dot{E} \) is given by

\[ E_y = \frac{B_1 V_1}{k_1} - \frac{B_1 k_2 V_2}{k_1} - U_x B - \frac{(1 - k_2) U_y B}{k_1} \]  

Equation A.11

For \( U_x \) and \( U_y \) sufficiently small, \( E_y \) is determined uniquely from the two velocity measurements \( V_1 \) and \( V_2 \):

\[ E_y = \frac{B_1 V_1}{k_1} - \frac{B_1 k_2 V_2}{k_1} \]  

Equation A.12

For the present experiment line-of-sight velocities were obtained by the radar for 8 range gates at 15 second intervals. Since the radar was scanning in elevation, the look angle changed by about 4° during the 15 second integration time. The distances to the range gates were slid along the line-of-sight during the scan so that velocity measurements could be obtained along lines of constant altitude. Each complete scan required 4 minutes and covered the region between the radar zenith and about 17° north elevation angle, as shown in Figure A-2. The velocity
Figure A-2
measurements along the line-of-sight were converted to perpendicular velocities according to Equation A.9.

As discussed above, measurement of the electric field requires an E-region velocity and an F-region velocity. For this experiment the F-region measurements were taken from the third range gate which was centered at about 200 km altitude. This ensured that the entire range was well above the collision-dominated portion of the ionosphere. The range gate 1 measurements were used for $V_1$. These were centered at about 105 km. The errors in these velocity measurements were computed using an empirical relation derived by Cullers et al. (1979). For the range gate 3 measurements, typical errors were 20 m/s, while for the range gate 1 measurements, they were about 15 m/s. These errors may be overestimated by a factor of 2 (R. Vondrak, private communication).

The two velocities used should ideally lie along the same magnetic field line. This means that for low elevation angles the two velocity measurements are not made at the same time and care must be taken that rapid temporal variations in the electric field do not distort the measurements. An alternative is to use two measurements made during the same 15 second integration interval. However, for low elevation angles $V_1$ and $V_2$ will not be along the same field line and may, in fact, be separated horizontally by as much as 50 km. This can be a serious drawback if
spatial gradients in the ionosphere are large. Just how serious these errors are depends to a large extent on the mobilities $k_1$ and $k_2$. For $k_1 \neq k_2$, Equation A.12 shows that the term in $V_1$ will usually be larger. Errors in $V_2$ due to spatial or temporal effects will have less effect than the statistical errors in $V_1$.

The 4° motion of the radar during an integration interval limits the spatial resolution of the velocity measurements. For low elevation angles adjacent line-of-sight velocities may be up to 20 km apart. To simplify the data reduction for the present experiment the flux tube scheme shown in Figure A-2 was adopted. The region spanned by the trajectory was divided into 20 km intervals numbered from 1 to 12 beginning with the horizontal range 0 to 20 km. The resolution of the velocity measurements provided at least one electric field measurement for each flux tube. In some cases the velocity measurements were close enough together to allow averaging of several values within the same flux tube.

The electric field measurements during the flight are shown in Figures A-3a and A-3b. Figure A-3a shows the east-west components while Figure A-3b shows the north-south components. Each plot shows the electric field as a function of time for one specific flux tube. Only the result for flux tubes 2 to 11 are shown. Each rectangle within the plots represents an electric field measurement.
Figure A-3a
Figure A-3b
for one of the three radar scans made during the flight. The horizontal extent of the rectangle indicates the time over which the measurement was made. The east-west components require only $V_2$ so the extent of the rectangles is 15 seconds. Since the north-south measurements used two velocities made during different integration periods, the time required was typically 1 to 1-1/2 minutes.

The vertical extent of the rectangles indicates the uncertainty in the measurements. For the east-west components, the uncertainties due to the 20 m/s random errors in the line-of-sight velocity measurements are about 1 mV/m. However, because of the projection factor in Equation A.9 these uncertainties can be twice as large, especially for flux tubes near the radar zenith.

For the north-south field components the random errors in the line-of-sight velocities produce uncertainties of 6 or 7 mV/m. However, these measurements are also affected by errors in the ion mobility coefficients $k_1$ and $k_2$. Since these quantities depend on the ionospheric collision frequencies which are poorly known, this is a potentially serious problem. The ion neutral collision frequency is given by

$$v_{in} = v_{ino} \times 10^{-12} N_n$$  

A.13
where $v_{\text{ino}} = 350/\text{sec}$ and $N_n$ is the neutral number density. Since the neutral density enters into this expression, an atmospheric model must be assumed. For this experiment the model used was from Banks and Kockarts (1973) with a thermospheric temperature of 1000°.

To assess the effects of errors in the collision frequency on the ion mobilities the constant $v_{\text{ino}}$ in Equation A.13 was halved and doubled. The three sets of mobilities generated in this manner are shown in Table A-1 for the four auroral regions of interest. Since $k_2 < .7$ for all regions, Equation A.12 shows that the resulting errors in $E_y$ will be largely functions of $V_1$ if $V_1$ and $V_2$ are comparable. Within the arc, where meridional velocities are small owing to the shorting out of the electric field, the errors are 1 or 2 mV/m. Only near flux tube 6 is $V_1$ large enough to produce uncertainties comparable to those arising from the statistical errors in the velocity measurements.
<table>
<thead>
<tr>
<th>$v_{\text{ino}}$</th>
<th>$k_1$</th>
<th>$k_2$</th>
<th>Diffuse Aurora</th>
<th>Dark Band</th>
<th>Arc</th>
</tr>
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<tr>
<td>187/sec</td>
<td>.324</td>
<td>.525</td>
<td>.304</td>
<td>.307</td>
<td></td>
</tr>
<tr>
<td>375/sec</td>
<td>.311</td>
<td>.351</td>
<td>.360</td>
<td>.473</td>
<td>.188</td>
</tr>
<tr>
<td>750/sec</td>
<td>.260</td>
<td>.203</td>
<td>.336</td>
<td>.263</td>
<td>.104</td>
</tr>
</tbody>
</table>

TABLE A-1
APPENDIX B

Comparison of Rocket and Radar Electric Field Measurements and Derivation of Neutral Winds

The open circles in Figures A-3a and A-3b represent the electric field components measured by the double probe carried by the payload. The horizontal position of the circles indicates the time at which the payload passed through each flux tube. Typical uncertainties in these measurements are shown by the error bars in the plots for flux tube 2.

For the east-west components the radar and rocket measurements agree fairly well. There are some differences in flux tubes 9 to 11 which must be due to the presence of a parallel ion drift. The drifts implied by these differences are discussed in Section 3.5.

For the north-south components the differences are much larger, especially for flux tubes 7 to 11. The three radar scan measurements indicate to what extent the electric field changed during the flight. It is apparent that these temporal variations are not large enough to account for the discrepancies in the $E_y$ measurements. Figure 3-12 shows a more compact comparison. Here the rocket and radar values for each flux tube are plotted as a function of horizontal distance. Thus, Figure 3-12 does not represent the electric field at one instant in
time, but is a composite plot incorporating measurements
taken over a 10 minute time span.

The obvious explanation for the large differences
in north-south electric field is the neutral wind term
which was neglected in the derivation of Equation A.12.
From Equation A.11 the neutral wind contributes a field
$E^n_y$ given by

$$E^n_y = -U_x B - \frac{(1 - k_1)U_y B}{k_1} \quad B.1$$

Since $k_1$ and $k_2$ are usually less than .5 the term
in $U_y$ will usually contribute more efficiently to $E^n_y$.
Taking $U_x = 0$, gives

$$E^n_y = - \frac{(1 - k_1)U_y B}{k_1} \quad B.2$$

In flux tube 8 the difference $\Delta E_y$ is about 30 mv/m and
$k_1 \sim k_2 \sim .3$. Thus, the neutral wind required is 240 m/s
southward. Within the aurora $\Delta E_y$ is 15 mv/m, $k_1 = .2$ and
$k_2 = .06$ so that $U_y$ must be 50 m/s southward. For flux
tubes 2 to 6 the small differences imply negligible neutral
wind flow.

There are two difficulties with this neutral wind model.
One is that it requires the velocity to change along the
direction of the wind. This is unlikely since such changes
must be accompanied by rapid vertical expansion or compres-
sion of the neutral atmosphere. The other problem is that the magnetometer detected a fairly intense westward electrojet flowing within the arc. The Westward electric field in the arc was only about 7 mv/m, which is not large enough to account for the observed current. A southward neutral wind contributes an eastward component to the current (Equation 3-12). Therefore, such a wind is not consistent with the magnetometer data.

On the other hand, if we let $U_y = 0$ in Equation A.13 then

$$E_{yn} = - U_x B$$

B.3

To account for the observed electric field differences the neutral wind must be westward at 360 m/s in flux tubes 9 and 10 and 600 m/s in flux tubes 7 and 8. These high velocities could easily explain the westward electrojet in the arc, but at the same time they decrease the eastward electrojet south of the arc to unacceptable magnitudes. Adding a small southward component to the wind reduces the magnitude of the westward component significantly. However, there still remains the problem of the seemingly large latitudinal gradient in the neutral wind. This difficulty can be resolved by recalling that in obtaining each line-of-sight velocity measurement, the radar integrates returns over a 96 km long range gate. For the region south of the arc, where the largest di-
crepancies in electric field measurements occur, this causes a serious distortion. For example, if the range gate is centered at a horizontal distance of 150 km, there is some contribution to the measured velocity from as far north as 190 km. Thus, northward ion drifts to the south of the arc are combined with heavily weighted southward drifts from within the arc producing reduced flux tube 8 line-of-sight velocity measurements.

A better way to compare the rocket and radar measurements is to convert the rocket electric fields to ion drift velocities. The ion velocity can be computed as a function of altitude from Equation A.3 with \( \vec{U} = 0 \). However, a suitable approximation can be made by using Equation A.10 instead. For \( E_x \) and \( E_y \) we use the rocket measured values and assume them to be constant at all altitudes along the flux tube. For one case the velocities computed in this manner were compared with the altitude dependent velocities given by Equation A.3. It was found that the velocities were similar in the altitude range 110 to 130 km. Since most of the contribution to the radar measurements comes from this altitude range, the use of Equation A.10 is justified.

The velocities computed from this equation are shown by x's in Figure B-1. By combining these velocities with the electron densities measured by the radar, we can perform the integration given by Equation A.1.
of this analysis are shown by triangles in Figure B-1. As expected, the greatest distortions occur for flux tubes 7 and 8. The line-of-sight velocities actually measured by the radar are given by circles in the figure. The latter two profiles are nearly identical except for an approximately constant offset of about 40 m/s.

The purpose of the above exercise was to verify that, despite the seemingly erratic differences between the rocket and radar electric field measurements, the discrepancies can be explained by a fairly uniform neutral wind flowing over the region. The required wind velocity is given most accurately by the difference in electric field measurements within the arc. This is true for three reasons. First, the high electron densities make the radar line-of-sight velocity measurements more accurate within the arc. Second, the look angle of the radar when observing the arc was nearly perpendicular to \( \overrightarrow{B} \) so that projection errors are minimal. And third, as shown in Figures A-3a and A-3b, the radar and rocket were measuring electric fields in flux tubes 9, 10, and 11 at about the same time.

From Equation A.11 the difference between the rocket and radar electric field measurements is given by

\[
E_y - E_{yr} = \Delta E_y^a = -U_x B - \frac{(1 - k_1) U_y B}{k_1} = 0
\]
where \( E_y \) is the double probe value and \( E_{yr} \) is the radar value. Since \( E_{yr} \) depends on \( k_1 \) and \( k_2 \) (Equation A.12) the difference \( \Delta E_y^a \) is a function of the mobilities. For the three mobility models given in Table A-1 the values of \( E_y^a \) are given below

\[
\Delta E_y^a = \begin{cases} 
11.3 \text{ mv/m} & \nu_{ino} = 187/\text{sec} \\
15.0 \text{ mv/m} & \nu_{ino} = 375/\text{sec} \\
24.8 \text{ mv/m} & \nu_{ino} = 750/\text{sec}
\end{cases}
\]

Some combinations of \( U_x \) and \( U_y \) which satisfy these three equations are shown in Table B-1. Although there is a wide range in the neutral wind velocities allowed by the uncertainties in the mobility coefficients, there are two other pieces of information which may be used to put additional restrictions on the model.

First, there are the magnetometer data which showed evidence of an eastward electrojet south of the arc and a westward electrojet within the arc. Since the westward electric field in the arc was only 6 mv/m a neutral wind of at least 100 m/s westward must be added to account for the current. On the other hand, if the westward component is greater than 150 m/s, it drastically decreases the magnitude of the eastward current south of the arc.

The second bit of information comes from the three position neutral wind measurements made 15 minutes before
<table>
<thead>
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<th>$U_y$ (m/sec)</th>
<th>$v_{ino} = 187$/sec</th>
<th>$v_{ino} = 375$/sec</th>
<th>$v_{ino} = 750$/sec</th>
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</thead>
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<tr>
<td>0</td>
<td>-460</td>
<td>-280</td>
<td>-210</td>
</tr>
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<td>-230</td>
<td>-180</td>
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<td>-130</td>
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<td>-80</td>
<td>-100</td>
</tr>
<tr>
<td>-50</td>
<td>10</td>
<td>-30</td>
<td>-70</td>
</tr>
</tbody>
</table>

**TABLE B-1**
the flight. These are shown in Figure 3-19. The small neutral wind velocities observed at this time also argue against excessively large winds at the time of the flight.

The most likely values for the neutral wind components are enclosed by boxes in Table B-1. It should be noted that these numbers use the difference in electric field measurements within the arc and thus apply to 5 or 6 minutes into the flight. There is some indication in Figure B-1 that these differences were smaller for the earlier flux tubes so that smaller neutral winds may be sufficient at the beginning of the flight. Section 3.6 presents additional arguments favoring a time varying neutral wind.
REFERENCES


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