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ROCKET-BORNE MEASUREMENT OF AURORAL
PARTICLE CURRENTS

By

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IX. REFERENCES
I. INTRODUCTION

A. Objectives of the Experiment

Experimental studies of the aurora have as their ultimate objective an understanding of all the processes which produce the observed auroral phenomena. Unfortunately, auroral phenomena are of such complexity and variability that a single experiment is restricted to a study of only one or a few particular auroral features.

This thesis presents the results of a rocket-borne experiment designed to measure the flux and directional distribution of the energetic particles responsible for the production of the visible auroral emission. The primary goal of the experiment was to measure the net electric current carried by these particles. In addition, it was expected that a measurement of these quantities while crossing a stable auroral feature and nearby regions would result in an improved description of auroral structure.

In this introductory section relevant characteristics of the aurora, auroral particles, and field-aligned current systems will be described in order to provide a context for the present experiment. Following sections describe the experiment and its results. Finally, the experimental results are discussed and applied to previous auroral measurements and theories.
B. The Aurora and Auroral Particles

The aurora is a visible emission in the upper atmosphere produced by the deposition of energy by charged particles. Studies of auroral phenomena have shown that the maximum occurrence of auroras is in a narrow oval belt encircling the geometric dipole pole as shown in Figure 1 (Akasofu, 1968; Feldstein, 1963). This oval is eccentric with respect to the dipole pole and its center is displaced towards the dark hemisphere. The location, shape, and orientation of the auroral oval results from the distortion of the earth's magnetic field by the solar wind.

Although the visual appearance of the aurora is generally quite variable, a characteristic stable feature is the occurrence of arcs and bands. These arcs are typically elongated in the magnetic east-west direction over a distance of hundreds or thousands of kilometers and have a north-south latitudinal extent of only a few kilometers. Such auroral displays are frequently accompanied by local magnetic disturbances caused by currents, known as the auroral electrojet, flowing within the ionosphere. Most of the currents are presumably confined to the visible auroral structures, which are regions of intensified ionization resulting from deposition of particle energy.
FIGURE 1

The auroral oval as determined by Feldstein and the outer boundary of trapping (after Akasofu, 1968)
During the evening and pre-midnight hours the auroral arcs characteristically remain stationary for tens of minutes with no rapid motion and little luminosity change. Such features are termed quiet arcs and their occurrence is usually referred to as the quiet or static phase of an auroral display. Sometimes such an aurora will enter a dynamic phase known as breakup characterized by very rapidly moving forms and very extensive, bright aurora. This transition usually occurs at a time near local midnight and the breakup display may develop and pass through its peak within a period of ten minutes or so.

Dynamic behavior of the aurora has been linked to general magnetospheric disturbances by the concept of the auroral substorm (Akasofu, 1968). In a substorm the process that produces quiet auroral arcs along the auroral oval is disturbed. The arc or arcs initially present are activated first in the midnight sector of the oval. Then, violent changes spread in all directions with a distinctive form in different local time sections of the oval.

The identification of the particles producing the
aurora has been dependent upon the technological means
to directly measure them. Prior to the development of
rocket-borne experiments, information about auroral
particles was obtained only by indirect methods. The
observed alignment of auroral rays with the geomagnetic
field lines implied that energetic charged particles
were involved in the emission. Auroras commonly occur
at an altitude of about 100 kilometers which corresponds
to the penetration depth of 10 keV electrons and 200 keV
protons. The gyroradii at these energies are 5 meters and
one kilometer for the electrons and protons respectively.
Since ray structure with thicknesses less than one kilometer
are frequently observed, electrons were inferred to be
the source of these thin structures. The first firm evi-
dence for energetic particle production of auroras was the
ground-based observation of doppler-shifted Balmer lines
in an aurora by Meinel (1950).

In the 17 years since the first rocket-borne de-
tection of charged particle flux into the auroral zone
by Van Allen (1957) there has been a multitude of direct
measurements of auroral particles by rocket and satellite
experiments. Some of the significant features of auroral
particle energy spectra and angular distributions will
now be discussed.
During the quiet or pre-breakup phase typical of early evening activity, the electron energies are limited almost exclusively to energies less than 10 keV with the differential energy flux approximately constant in the energy range of 1-10 keV. Peaks in the differential energy spectra have been observed at 3.8 keV (Evans, 1967) and 10 keV (Chase, 1967). Typical measured spectra are shown in Figure 2 (after Whalen and McDiarmid, 1969). Although the measured fluxes depend on the intensity of the specific event and spectral shapes may vary from aurora to aurora, data comparisons like Figure 2 are useful examples of "typical" auroral features. Proton measurements during quiet periods are less numerous than corresponding electron measurements. Proton spectra measured by Chase (1968) and Whalen (1967, 1968) are shown in Figure 3.

Measurements during auroral breakup or substorms indicate that the majority of the particle energy is carried by electrons with energy in the range 1-20 keV. Recent observations also indicate that the bulk of the incoming electron energy resides in a "near-monoenergetic" beam in the energy range 4 to 10 keV, with a differential flux of roughly $10^8 - 10^9$ cm$^{-2}$-sec-ster-keV. Westerlund (1968) measured an auroral electron spectrum that was
FIGURE 2

Typical electron differential energy spectra measured in quiet, pre-breakup aurora. The solid line is a spectrum of the form

\[ N(E) = N_0 E^{-1} \]
FIGURE 3

Differential energy spectra of pre-breakup protons.
double peaked, with a peak in the 6-10 keV range and a further rise in intensity below 1 keV with a second peak near 100 eV. In addition, the 6-10 keV peak disappeared from the spectrum in the diffuse aurora between the arcs leaving a continuum characterized by a power law of the form \( N(E) = N_0 E^{-1.3 \pm 0.3} \) in the energy range 100 eV to 25 keV. In general, electrons with energy greater than 20 keV have been found to be more variable in space and time than the electrons in the < 10 keV range. Protons have usually been reported to be less numerous than electrons in breakup auroras, although fluxes as high as \( 8 \times 10^{2} \) /cm\(^2\)-sec-ster-keV have been detected in the energy range 1-20 keV (Bernstein et al., 1969). Reasoner et al. (1968) found the differential spectrum of protons in the energy range 90 keV to 400 keV to be given by

\[
N(E) = 8 \times 10^{-5} 2 E^{-2} \text{ /cm}^{-2} \text{-sec-ster-keV}
\]

where \( E_0 \) equals 100 keV.

Rocket-borne measurements of electron angular distributions indicate a general tendency to peak normal to \( \vec{B} \), but becoming more isotropic with increasing intensity. It is usually found that for both low and high energies the upward moving flux is about 10-20% of the downward moving
flux. However, observations of anomalously high back-scattered fluxes (up to 120% of the precipitated fluxes) have been reported by Cummings et al. (1966) and McDiarmid et al. (1961).

Satellite measurements of auroral energy particles are useful in mapping out the persistent features of particle precipitation in the auroral region. The first polar satellite measurements by O'Brien (1962) observed that the high-latitude trapping boundary of electrons ($E > 40$ keV) undergoes a diurnal variation which agrees well with that of the visual auroral oval. Later satellite measurements by McDiarmid and Burrows (1965) and the Lockheed group (Johnson et al., 1966; Sharp and Johnson, 1967) showed that this hard electron precipitation occurs over a narrow latitudinal extent ($\sim 2^\circ$) along the night-side auroral oval. Observations within two hours of local midnight presented by Burch (1968) revealed two latitudinal regions of precipitation on the night side. The lower latitude regions ($L \sim 5-8$) contained auroral type electron spectra. Contiguous to and poleward of this region is a zone of much softer electrons with large spatial and/or temporal variations. Night-side proton precipitation regions were found to be similar, although not corresponding in spatial location with the electron
zones. Bursts of highly structured precipitation in the upper soft electron zone were reported by Hoffman (1968).
C. **Field-Aligned Currents and Auroras**

The existence of currents flowing parallel to the geomagnetic field lines was first suggested by Birkeland in 1908 as a possible driving mechanism for the polar magnetic disturbances associated with the auroral electrojet. More recently such a field-aligned current system has been studied as a possible link between the outer magnetosphere and the polar ionosphere.

For several reasons (Boström, 1964) the auroral electrojet cannot be driven by ionospheric dynamos, such as upper atmospheric winds, but must be driven by electric fields in the magnetosphere. It is believed that a charge separation occurs in the outer magnetosphere which results in a potential difference between field lines. This potential difference is subsequently transported to the ionosphere along the equipotential field lines. In the ionosphere the conductivity is sufficiently high to allow a transverse current. The result is a current system consisting of current flowing along the earth's field lines in the magnetosphere and current flowing across the earth's field lines in the ionosphere. The exact geometry and physics of the field-aligned current system
have not been determined, although several models have been proposed.

A current system of the kind shown in Figure 4 was first suggested by Birkeland. He explained the auroral electrojet by a current system with two vertical currents in opposite directions connected by a horizontal component. Boström (1964) analyzed such a configuration in which the auroral electrojet is driven by a strong electric field ($\sim 25$ mV/m) directed parallel to the ionospheric current. A Hall current results which flows transverse to the auroral electrojet. As the conductivity is much lower outside the electrojet, the Hall current is inhibited and produces a polarization electric field. The net effect is an increase of the effective conductivity which gives rise to an additional Pedersen current along the arc.

The total current flowing in the auroral electrojet may be typically $3 \times 10^5$ amperes. The horizontal current is not carried by the precipitating auroral particles, but rather by the thermal ions in the ionospheric E-layer. The auroral particles are responsible for the conductivity enhancement within the electrojet. In Birkeland's original model the two vertical line currents existed at the ends of the electrojet. However, Alfvén (1963) has suggested that the inflow and outflow of current may occur continuously along the auroral zone.
FIGURE 4

Auroral electrojet driven by a Birkeland current system
with a vertical sheet current density of about 0.1 amp/m. This vertical sheet current produces a magnetic disturbance of only 60 $\gamma$.

Boström (1964) has proposed an alternate configuration shown in Figure 5. In this model any charge accumulated at the boundary of the arc is assumed to be able to escape into the magnetosphere along the field lines. A Pederson current flows northward across the electrojet and is closed by sheet currents flowing from the southern and northern edges of the electrojet. The required ionospheric electric field is 56 mV/m perpendicular to the arc. Bostrom estimates that the current flowing along a single 10 km thick auroral arc is $3 \times 10^4$ amp. This leads to a height-integrated Hall current density of 3 amp/m and comparable vertical currents at the northern and southern edges of the arc. The sheet currents flow upward from a height of 95 km, and are about 1 km thick. The transverse magnetic disturbance due to these current sheets will be about 3000 $\gamma$.

The field-aligned current systems discussed above, as well as others that have been proposed, derive their ultimate driving source from a charge separation in the
FIGURE 5

A field-aligned current system closed by sheet currents at the edge of the auroral electrojet (Boström, 1964)
magnetosphere. A variety of mechanisms have been proposed to provide such charge separation.

Fejer (1963), Gottlieb and Fejer (1967) have argued that the interaction of magnetospheric motions with the trapped radiation can lead to steady auroral electrojet currents. The currents are driven by electric fields that originate in charge separation produced by the difference between motions of the high-energy trapped particles and the low energy magnetospheric plasma.

Cummings and Dessler (1967) have suggested a field-aligned current configuration of the Birkeland type which is driven by an asymmetric (partial) ring current. This model was proposed to explain the low latitude diurnal daily variation. Meng and Akasofu (1969) have also proposed a Birkeland current system driven by a partial ring current to explain the magnetic disturbance observed in a polar substorm.

Schield, Freeman and Dessler (1968) have developed a mechanism, originally proposed by Alfvén (1950), which can provide a source for field-aligned currents at auroral latitudes. The drift of plasma toward the earth from the plasma sheet in the earth's magnetospheric tail is terminated by a sharp inner boundary known as the Alfvén layer. A charge separation arises at this boundary because of the different drift paths of electrons
and ions. The charge separation produces an electric field that is perpendicular to \( \mathbf{B} \) and is transmitted along the lines of force to the ionosphere as shown in Figure 6. It was also found that the thickness of the Alfvén layer corresponds to the width of the auroral oval.

Current systems driven by plasma pressure gradients in the magnetosphere have been suggested by Boström (1967), Taylor and Perkins (1969), and Vasyliunas (1970).

The observational evidence for the existence of field-aligned currents is meager. The magnetic perturbations observed at the earth's surface due to the auroral electrojet can always be explained (mathematically) as resulting from currents flowing only horizontally in the ionosphere. Thus, it is impossible to draw any definite conclusions about the existence of a field-aligned current from ground-based observations alone.

As will be shown below, the main effect directly produced by a field-aligned current of the intensity required in the above models is a change in direction but not in magnitude of the field. Therefore, observation of the magnetic effects of these currents
FIGURE 6: The Alfven layer and its connection to the auroral ionosphere (after Schield et al., 1969)
requires a vector instrument on a vehicle whose attitude is precisely controlled or measured. Zmuda et al. (1966, 1967) have flown such an instrument on a polar satellite orbiting at an altitude of 1100 km. They regularly detected localized transverse field disturbances of the order of 30 to 400 γ in a region found to correspond with the auroral oval. Substructure was seen in this region although no attempt was made to correlate it with visual aurora. Cummings and Dessler (1967) have shown that such localization requires the disturbances to be derived from a field-aligned current system.

The measurements of Zmuda are the only reported direct observations of the effects of a field-aligned current in the auroral region. However, other observations have been made which are consistent with the existence of a field-aligned current system. For example, Atkinson (1967) was able to reproduce the complicated distribution of the magnetic vectors in and around regions of active aurora only by means of a combination of field-aligned currents and Hall currents. Also, low-energy (2 keV) electron bursts with maximum flux directed along the field lines have been detected by an auroral satellite experiment (Hoffman and Evans, 1967). Hoffman and Evans argue that the distributions and energy spectra of these bursts indicate the existence
of electric fields parallel to the magnetic field lines. Large electric fields ($\sim 20$ mV/m) parallel to the magnetic field were measured by Mozer and Bruston (1967) in a rocket-borne auroral experiment. However, barium cloud experiments in the auroral regions have found the parallel electric field to be $\leq 100$ $\mu$V/m (Mende, 1968; Lust, 1968). In general, both rocket-borne (Aggson, 1969) and barium cloud experiments (Wescott et al., 1969; Haser, 1967) determined the electric field transverse to $B$ to be about 10 to 30 mV/m outside the aurora and very low ($\leq 5$ mV/m) within the aurora. However, it should be noted that indirect observations like the above are inconclusive evidence for the existence of a field-aligned current system.

As was discussed above, the field-aligned current system has been postulated as the driving mechanism of the auroral electrojet. The electrojet is presumed to be localized to the arc because of the enhanced ionization and conductivity resulting from energy deposition by the auroral particles. Assuming the spatial coincidence of auroral precipitation and the electrojet, we may seek to identify the auroral particles as the charge carriers of the field-aligned current. It is not known whether the currents along the field lines are carried
by the high energy particles (> 1 keV) that produce the aurora, or if they are carried by low-energy particles of possibly ionospheric origin. On the basis of theoretical and observational flux distributions, Schield (1968) has concluded that the current is carried by low-energy (E ≤ 100 eV) ionospheric protons and magnetospheric electrons. However, it should be noted that until a measurement of the net flux of auroral particles is made, the identification of the charge carriers is largely unresolved.
II. DESCRIPTION OF THE EXPERIMENT

A. Experimental Technique

The purpose of this experiment is to investigate the relationship between field aligned currents and auroral particles. In the experiment two separate methods were used to obtain independent measurements of the field aligned current:

1) A direct determination of the current carried by the auroral particles by measuring the net flux of charge;

2) A deduction of the total current magnitude and location from a measurement of the induced magnetic field.

In general, determining a current from the induced magnetic field, \( \vec{B} \), requires knowledge of the curl of \( \vec{B} \). This requires a measurement of the field at a number of neighboring points in different directions from the point considered. However, if the currents flow in simple geometries such as a sheet or a line, the current magnitude and direction can be deduced from measurements of \( \vec{B} \) along a path through the
current region. As discussed above, the transverse disturbance field detected by Zmuda's satellite experiment was of the order of 100\(\gamma\). Such field strengths are also consistent with theoretical predictions based on arc structure. This disturbance field results in a negligible change in the total magnetic field (\(\Delta B \sim 0.1\gamma\)) and a change in field direction of \(\sim 0.1^\circ\). Therefore, detection of these currents requires a directional measurement of the magnetic field with such an accuracy. A description of the vector magnetometer system used in this experiment and its results are reported elsewhere [Cloutier et al. (1970); Park (1970)] and will not be discussed in this thesis.

In order to measure the current directly by determining the net directional charge flow it is necessary to measure the total number fluxes of electrons and protons separately as a function of direction. This requires instrumentation which can:

1) detect auroral particles over a wide energy range;
2) measure number fluxes of positively and negatively charged particles separately;

3) measure the directional distribution of the particle velocities.

In order to measure the total current one needs to know the net flux over the entire energy range of interest. Accurate measurement of fluxes of very low (thermal) energy particles is experimentally very difficult with a rocket-borne system. For this reason it was decided to limit coverage to auroral particles of sufficient energy to produce the visible auroral emission by penetrating to low altitudes. This restriction is also justified by the desire to be able to extrapolate the current above the atmosphere, which necessitates measuring the primary auroral particles rather than the lower energy secondaries. In the remainder of this thesis reference to auroral energy particles or energetic particles implies particles with energy greater than 1 keV. This is a somewhat arbitrary restriction dictated primarily by instrumental limitations, since particles of lower energy are present in auroras. However, a current measurement limited to energetic particles still has scientific value. If there is a direct correlation between the auroral particles and the field-aligned
current, then measurement of the auroral particle currents will provide information concerning the spatial configuration of the field-aligned currents. Also, comparison of the energetic particle current with the total current deduced from the independent magnetometer measurement will reveal what fraction of the field-aligned current is carried by the energetic auroral particles.

In order to measure particle flux over a wide energy range instruments were designed with broad energy bandpasses. In doing this spectral resolution is sacrificed in order to obtain more complete information as to total number fluxes. Previous measurements discussed in the introductory section have shown the auroral particles in the energy range 1-20 keV are most important because of their quantity and the occurrence of monoenergetic peaks in this region.

The second requirement set by the experimental goals is the measurement of number fluxes separately by charge sign. This eliminates total energy detectors and requires utilization of a variety of detectors in order to measure both protons and electrons. As discussed in the introduction, previous auroral particle measurements have generally found that protons are less numerous than electrons. However, it should
be noted that Chase (1968) and Bernstein et al. (1969) detected comparable fluxes of electrons and protons. Although this may be unusual, it does indicate that measurement of both protons and electrons is necessary in order to obtain a definitive current measurement.

In order to measure net flux along the field line, we need to know the flux of both downward moving particles and the upward moving particles which are either back-scattered from the atmosphere or may have mirrored below the altitude of measurement. The angle between the field line and the particle velocity vector is referred to as the pitch angle. The pitch angle distribution of the particle velocities is measured by using detectors pointing up and down the field lines. If the rocket axis is aligned at an angle $\theta$ with respect to the geomagnetic field line and the detector is mounted at an angle $\varphi$ with respect to the rocket spin axis, then during each rocket rotation the particle detectors will roll scan a range of pitch angles from $|\varphi-\theta|$ to $|\varphi+\theta|$. Complete pitch angle coverage results for detectors mounted at 45° and 135° and a field line-rocket axis angle of 45°.

In order to provide pitch angle distribution data the detectors must be directional. Highly-directional detectors provide the best angular data, but also reduce
the counting rate and, consequently, the statistical accuracy. An opening angle of 20° was chosen as providing both reasonable angular resolution and adequate counting rates.

The selection of quantity and type of instruments was ultimately dictated by consideration of system complexity and limitations on payload size and weight. The following instruments were used:

1) Channeltron detectors preceded by electrostatic curved-plate analyzers for energy resolution to measure particles in the energy range 2-18 keV. Four instruments measure protons and electrons separately moving up and down the field lines.

2) A solid-state proton detector to measure proton fluxes in the energy range 100 to 1000 keV. A broom magnet is used for electron rejection.

3) A Geiger tube which responds to both electrons with energy > 50 keV and protons with energy > 700 keV.

The basic detector specifications are summarized in Table 1.
<table>
<thead>
<tr>
<th>Detector</th>
<th>Particle Type</th>
<th>Φ</th>
<th>Energy Range</th>
<th>Geometric Factor (Θ)**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channeltron EP</td>
<td>precipitated electrons</td>
<td>45</td>
<td>2&lt; E&lt; 18 keV</td>
<td>15.3x10^{-6} cm²-sr-keV</td>
</tr>
<tr>
<td>ChanneltronEB</td>
<td>backscattered electrons</td>
<td>135</td>
<td>2&lt; E&lt; 18 keV</td>
<td>10.2x10^{-6} cm²-sr-keV</td>
</tr>
<tr>
<td>Channeltron PP</td>
<td>precipitated protons</td>
<td>45</td>
<td>2&lt; E&lt; 18 keV</td>
<td>5.1x10^{-6} cm²-sr-keV</td>
</tr>
<tr>
<td>ChanneltronPB</td>
<td>backscattered protons</td>
<td>135</td>
<td>2&lt; E&lt; 18 keV</td>
<td>3.9x10^{-6} cm²-sr-keV</td>
</tr>
<tr>
<td>Solid-State</td>
<td>precipitated protons</td>
<td>45</td>
<td>80 keV&lt; E&lt; 1 MeV</td>
<td>1.5x10^{-2} cm²-sr</td>
</tr>
<tr>
<td>Geiger tube</td>
<td>precipitated electrons</td>
<td>45</td>
<td>50 keV&lt; E&lt; E_e</td>
<td>7x10^{-3} cm²-sr</td>
</tr>
<tr>
<td></td>
<td>and protons</td>
<td></td>
<td>700 keV&lt; E_p</td>
<td></td>
</tr>
</tbody>
</table>

* Φ is the detector orientation angle with respect to rocket spin axis

** Ξ = \int_{2 keV}^{18 keV} G(E)dE for channeltrons
B. Design and Calibration of the Particle Detectors

1. Channeltron Proton-Electron Detector

The measurements of auroral particles of low energy (< 50 keV) requires an instrument having very little or no entrance window surrounding the active volume of the detector. The channel electron multiplier (the Bendix C-type Channeltron®), a windowless detector, is used in the present experiment.

The channeltron is essentially a hollow glass tube with a highly resistive coating ($10^9 \Omega$) on the inside. It is a small c-shaped device with a channel outside diameter of 2 mm., a radius of curvature of 2.16 cm., and an end opening area of approximately 0.8 mm$^2$. The aperture end of the channeltron is at ground potential and the collector end is at approximately +3500 volts. When a particle strikes the coating in the channeltron, it produces secondary electrons which are accelerated by the electric field along the channel until they strike the coating and again release more electrons. In this way, one particle entering the aperture can cause $10^8$ electrons to reach the collector end of the channeltron. These electrons at the collector cause a pulse to be passed
through a coupling capacitor to the pulse amplifier.

The channeltron detector measures particle flux but provides no information as to particle energy. The identification of the particle energy and type (i.e. charge sign) is accomplished by the use of cylindrical curved-plate electrostatic analyzers (Figures 7 and 8). The analyzer curvature permits particles with a certain energy-to-charge ratio (E/q) to travel circular trajectories and reach the channeltron detector. Following a design of Frank (1965), three cylindrical curved plates are used to form two 35° analyzers for measurement of proton and electron fluxes separately. The two outer plates are grounded and the center plate is supplied with a positive potential of approximately 500 V. The outer analyzer will accept electrons of appropriate energy and the inner analyzer will measure the fluxes of positive particles of a comparable energy.

An analyzer with cylindrical plates of radius $r_1$ and $r_2$ and applied voltage $V$ between the plates will pass particles with an energy to charge ratio such that

$$\frac{E}{q} = \frac{V}{2 \ln(r_2/r_1)}$$
FIGURE 7

Schematic representation of electrostatic analyzers. The side plates are grounded and a positive voltage is applied to the center plate. Only portions of the C-shaped channeltrons are shown.
FIGURE 8

The electrostatic curved-plate analyzer
Because of the finite dimensions of the analyzer, there is a range of particle energies that will pass through the deflection plates and reach the detector. The width of the energy bandpass is determined by the gap width of the analyzer plates, the arc length, and the placement of the channeltron detector. The collimating slits in front of the analyzer help to define the angular response of the instrument. The analyzer plates are serrated and blackened to reduce particle and light scattering within the instrument.

Electrostatic analyzers are often designed to have a narrow bandpass. The voltage between the plates is then stepped in order to obtain a differential spectrum (Frank, 1965; O'Brien et al., 1967; Hoffman and Evans, 1967a). In the present experiment we would like to obtain an integral measurement of the flux over a wide energy range. In addition, time spent over the arc may be shorter than the time required for a spectral scan (~10 secs.). Also, stepping of the voltage might create interference with the magnetometer. For these reasons the energy bandpass of the instrument is made as large as possible and the analyzer voltage is not stepped.
Calibration of the instrument consists of determining the response of the instrument to particles of various energies at various angles of incidence. This is accomplished by exposing the instrument to an electron beam and measuring the count rate for varying angles of incidence.

A uniform, four-inch diameter, monoenergetic electron beam of adjustable energy and intensity was used for the measurement of the energy passbands and angular response. The electron beam is generated by accelerating photoelectrons ejected from a twelve-inch diameter gold-surfaced aluminum plate which is illuminated with ultraviolet light from mercury lamps. The accelerating potential is applied between the aluminum plate and a four-inch diameter grounded screen which serves as the exit aperture. Between the grounded screen and the aluminum plate, and connected at equal voltage intervals along a resistive divider, are eleven concentric aluminum rings with inside diameters of ten inches. The resulting electron beam is nearly monoenergetic with energy variable up to 30 keV. Helmholtz coils situated outside the chamber are used to cancel the earth's magnetic field.

The usual calibration procedure was to maintain a
constant beam energy while varying the angle of incidence by rotating an angular sweep fixture on which the instrument was mounted. The pivot for this angular variation was at the front aperture of the unit so that the same portion of the beam was sampled during the entire angular sweep. A Faraday cup was used to measure the beam intensity both before and after each angular scan. The angular response was measured chiefly in the plane of symmetry (XY plane) of the analyzers by varying the angle $\theta$ as shown in Figure 7. Typical response curves for the detector EP (precipitated electrons) are shown in Figure 9. In general, the angular width in this direction to the 10% point was about 5°. Also, the angle of peak response is seen to depend on energy. Such angular response curves were measured at 0.5 keV intervals between 1.5 keV and 22 keV and at 0.5° angular increments. Response in the transverse direction (XZ plane) was found to be more uniform and have a broader angular width as shown in Figure 10. Calibration in this transverse direction was not as extensive as in the symmetry plane due to time limitations. All calibrations were carried out at fairly low count rates of a few thousand counts per second to avoid saturation effects.
FIGURE 9
Angular response of channeltron detector EP in the plane of symmetry (XY plane of Figure 7).
FIGURE 10

Transverse response of channeltron detector EP. \( \phi \) is the angle in the XZ plane of Figure 7.
From the response curves of the instrument as a function of energy and direction we would like to compute a relation between the counting rate and the incident particle flux. The observed count rate, \( R \), is given by

\[
R(\text{counts/sec}) = \int \int r(\theta, \varphi, E) dE d\Omega
\]  

(1)

where \( r(\theta, \varphi, E) \) is the number of counts in a particular direction for a particular energy (counts/sec-ster-keV), and \( \Omega \) indicates solid angle. The count rate is related to the incident flux by

\[
R(\text{counts/sec}) = \int \int G(\theta, \varphi, E) N(\theta, \varphi, E) dE d\Omega
\]  

(2)

where \( N(\theta, \varphi, E) \) is the beam flux in a particular direction and energy (particles/cm\(^2\)-sec-ster-keV) and \( G(\theta, \varphi, E) \) is a directional geometric factor (cm\(^2\)).

If we assume that the incident beam flux is monoenergetic within \( dE \) of a particular energy and unidirectional to within \( d\Omega \) of the incident direction,
then the current in amperes, $I_o$, measured by the Faraday cup of area $A$ is related to the incident flux by

$$\frac{I_o}{eA} = N(\theta, \varphi, E)\,d\Omega dE.$$ 

In the calibration of the instrument we measure $\mathcal{R}(\theta, \varphi, E) = r(\theta, \varphi, E)\,d\Omega dE$ for each $\theta, \varphi, E$. By equations (1) and (2) we see that

$$r(\theta, \varphi, E)\,d\Omega dE = G(\theta, \varphi, E)N(\theta, \varphi, E)\,d\Omega dE$$

Therefore,

$$G(\theta, \varphi, E) = \frac{r(\theta, \varphi, E)\,d\Omega dE}{N(\theta, \varphi, E)\,d\Omega dE} = \frac{\mathcal{R}(\theta, \varphi, E)\,eA}{I_o}$$

Thus, measurements of $\mathcal{R}$ and $I_o$ allow us to determine $G(\theta, \varphi, E)$.

The observed count rate for an isotropic flux such that $N(\theta, \varphi, E) = N(E)$ independent of $\theta$ and $\varphi$ is given by
\[ R = \int_{E}^{N(E)} G(\theta, \varphi, E) \, d\Omega \, dE = \int_{E}^{N(E)} G(E) \, dE \]

where \( G(E) = \int_{\Omega} G(\theta, \varphi, E) \, d\Omega \). \( G(E) \) is called the energy geometric factor. For our purposes, the assumption of an isotropic flux means that we are assuming that the flux is uniform over the angular response region of the instrument. This corresponds to isotropy over approximately 10° in pitch angle and about 20° in azimuthal direction. If necessary, as in the case of a pitch-angle distribution with fine structure, corrections can be made by an iterative procedure.

\( G(E) \) is evaluated from the calibration data by replacing the integration over solid angle by a double sum over the directional elements:

\[ G(E) = \frac{eA}{I} \int_{\Omega} R(\theta, \varphi, E) \, d\Omega = \frac{eA}{I} \sum_{\theta} \sum_{\varphi} R(\theta, \varphi, E) \Delta \theta \Delta \varphi \]

For computational ease, the double sum is split into two components:
\[ \sum R(\theta, \varphi, E) = \sum_{\theta} R(\theta, \varphi, E) \frac{\Xi(\theta, \varphi, E)}{\Xi(\theta, \varphi, E)} \]

The sum over \( \theta \) is obtained from the angular response data in the symmetry plane and the sum over \( \varphi \) is obtained from the transverse response data by assuming the transverse response to be independent of \( \theta \).

The energy geometric factors obtained in the above manner are shown in Figure 11 for the channeltron unit viewing precipitated electrons and in Figure 12 for the channeltron unit measuring backscattered electrons. The variations in the geometric factors between the two units is presumably due to differences in the placement and alignment of the channeltrons between the deflection plates, which is a critical factor in establishing the energy bandpass.

No source of low energy protons was available for the calibration of the proton-accepting sections of the instruments. The proton units were calibrated with electrons by reversing the polarity of the deflection plates and the energy geometric factors were calculated as above. The energy geometric factor
FIGURE 12: Energy geometric factors for channeltron detector EB (backscattered electrons).
depends upon the physical geometric factor of the electrostatic analyzers and the efficiency of the channeltron detectors. Efficiency, ε, is defined as the ratio of the number of detector output pulses to the number of particles striking the detector. Assuming that the electrostatic analyzer has the same characteristics for protons as electrons, the only adjustment to the energy geometric factor is multiplication by the ratio of channeltron proton efficiency to channeltron electron efficiency. Measurements of the absolute efficiency of channeltrons for protons and electrons have been published by Egidii et al. (1969) and Sharber et al. (1968). Both groups determined a proton efficiency of about 25% at 1 keV rising to about 50% at 4 keV whereupon it remains constant to 30 keV. A relative efficiency for protons which has the same general shape has been reported by Burrous et al. (1967). The measured electron efficiencies were from 65-90% at 1 keV decreasing gradually to about 30% beyond 10 keV. A similar electron efficiency has been reported by Hoffman and Evans (1967a) while Frank (1965) has reported a somewhat steeper energy dependence. In our calculations we use the average of the efficiencies determined by Sharber and by Egidii. The resulting ratio of
channeltron proton efficiency to electron efficiency is shown in Figure 13. The energy geometric factors for the proton units determined from the analyzer calibration and adjusted by the proton-electron efficiency are shown in Figure 14.

Electron rejection of the proton units was measured by comparing the electron count rates at both polarities and was found to be greater than $10^4$. This is also an indication of the sensitivity of the analyzers to scattering within the plates.

The absolute accuracy of the calibration is difficult to evaluate. The main uncertainty is a result of incomplete knowledge of the transverse response of the analyzers. The absolute accuracy of the energy geometric factors is estimated to be a factor of 3. For example, for unit EP, $G(E=6 \text{ keV}) = (1 - 0.7) \times 10^{-6} \text{ cm}^2\text{-ster}$. The proton unit calibration also depended on an assumed proton-electron efficiency of the detectors. From the stated accuracy of the published efficiency data, it is estimated that an additional factor of two uncertainty is introduced into the calibration of the proton units.

Since identical assumptions about the transverse response of the analyzers were made in the reduction
FIGURE 13: Relative channeltron efficiency, $\varepsilon$, for protons and electrons
FIGURE 14: Energy geometric factors for channeltron detectors PP (precipitated protons) and PB (backscattered protons).
of the calibration data, the relative accuracy of the individual units is better than the absolute accuracies of the instruments.

2. The Solid-State Proton Detector

The flux of protons in the energy range 75 keV to 1 MeV is measured by an instrument employing a solid-state surface barrier detector as its detecting element. The instrument is collimated to achieve directionality and a magnet is used for low-energy electron rejection. A schematic diagram of the instrument is given in Figure 15 and the flight instrument is shown in Figure 16.

The surface barrier detector used is a commercially prepared (Ortec, Inc.) detector consisting of an extremely thin p-type layer on the sensitive face of a high purity n-type silicon wafer. When a charged particle enters a semiconductor detector, it creates free electron-hole pairs by losing energy at a rate of 3.5 electron volts per electron-hole pair. The sensitive (depletion) region of the detector corresponds to that portion of the silicon that contains an electric field resulting from an externally applied reverse bias on the diode. Free
FIGURE 15
The solid-state proton detector
Figure 16

Photograph of the payload section containing the particle detectors. The upward-pointing detectors are the solid-state detector (above) and the Geiger tube (below).
charge carriers created in this region by the ionizing radiation are separated under the influence of the electric field, and the resulting net charge represents the basic source of information about the number of charge carriers created by the incident radiation. The detector is operated with a bias voltage of 31 volts which results in a depletion depth of 200\mu.

The two electrical contacts to this diode are made to the p-type surface through a thin gold film approximately 40\mu g/cm\(^2\) thick and to the n-type silicon through a thin aluminum contact on the back surface. This gold layer constitutes material which the particle must traverse before entering the depletion region since energy loss in this layer does not produce any charge output. The energy loss in the gold dead layer has been calculated to be 4 keV for a 90 keV proton.

Since the pulse amplitude coming from the solid-state detector is rather small, amplification is needed so that the pulses can be handled by the data system. For example, a 350 keV proton will release \(10^5\) electrons in the detector, or \(1.6 \times 10^{-14}\) coulombs of charge. For a typical detector capacitance of 10 pf, this charge will produce a voltage of only 1.6 mV.
In a solid-state detector all information concerning the energy deposited by the incident particles is contained in the number of charge carriers they create in the detector. Since the capacitance of a solid-state detector varies when the applied bias is changed, the voltage pulse for a given charge pulse would vary also. For this reason a charge-sensitive amplifier is used to convert the charge output of the detector to a voltage pulse which is independent of the input capacitance.

Following the charge-sensitive amplifier a window discriminator is used to count pulses whose amplitude lies between two levels. The upper level is set for an amplitude equivalent to the pulse size produced by a 1000 keV proton. The amplitude of the lower discriminator is set as small as possible in order to detect the lower energy protons. The lower discriminator level is limited by the system noise which is produced both within the detector and within the amplifier. Figure 17 indicates the transmission levels of the window discriminator and, corrected for dead layer losses, the effective bandpass of the instrument. The count rate due to detector and amplifier noise was determined to be approximately two counts per second.
FIGURE 17: Energy bandpass of the solid-state proton detector. Dotted line includes correction for dead layer energy loss.
In order to provide pitch angle distribution data the solid-state proton detector is made directional by the use of collimators to restrict its field of view to approximately 15° full opening angle. As shown in Figure 15, collimation is provided by aluminum knife edges of thickness 0.21 gm/cm², corresponding to the range of 600 keV electrons and 12 MeV protons.

The geometric factor, $G$, is the proportionality constant between the particle flux, $F$, and the detector counting rate, $R$, so that

$$F(\text{particles/cm}^2\text{-sec-ster}) \cdot G(\text{cm}^2\text{-ster}) = R(\text{particles/sec})$$

For cylindrical symmetry and a viewing half-angle, $\theta$, the geometric factor for a detector of area $A$ and efficiency $\varepsilon$ is approximately given by

$$G = 2\pi A\varepsilon (1-\cos\theta) \text{cm}^2\text{-ster}$$

For a completely efficient detector with an effective area of 0.27 cm² and 7.5° half-angle, this relation yields
a geometric factor of \( G = 0.015 \text{ cm}^2\text{-ster} \).

Because of the finite thickness of the detector, some higher energy particles which have a low ionization loss \( (dE/dx) \) will deposit energy in the detector within the discrimination levels. Using specific energy loss data from Ortec (1964), we can compute energy loss curves for particular detector thicknesses. Figure 18 indicates the energy deposited in a 200\( \mu \) depletion region as a function of proton energy. From this figure it can be seen that the 200\( \mu \) detector will be sensitive to 20-500 MeV protons. Measurements on a space probe have determined the flux of galactic cosmic rays for proton energies greater than 10 MeV to be approximately 4 particles/cm\(^2\)-sec (Anderson, 1968). For a detector of area 0.5 cm\(^2\) the counting rate due to cosmic ray contamination is then less than 2 counts/sec.

The most serious potential source of data contamination in the solid-state detector is electron flux. The electron response of the 200\( \mu \) depletion depth detector is shown in Figure 19. It should be noted that these values are for traversal of a thickness of silicon equal to the detector depletion depth. Due to scattering of the electrons within the detector, there is a probability of an electron losing its entire energy
FIGURE 18: Proton energy loss in traversing 200\(\mu\) of silicon.
FIGURE 19: Electron energy loss in traversing 200\mu of silicon.
within the detector, even if its range exceeds the detector thickness. Since the electron flux in an aurora is so much greater than the proton flux, some form of electron rejection mechanism is required in order to obtain a meaningful proton measurement.

The electron rejection mechanism employed in the solid-state proton detector consists of a broom magnet in front of the detector which will significantly deflect the electrons but will have an insignificant effect on the heavier protons. The field configuration and magnet arrangement are shown in Figure 15. Four ceramic magnets magnetized perpendicular to their face are enclosed in a soft iron holder. The soft iron section increases the interior field within the pole face gap and reduces the exterior stray field. The interior field was a maximum of 300 gauss on the center line of the instrument and the exterior stray field was less than 0.5 gauss. From measurements of the interior field strengths, it was calculated that the cutoff energy for normally incident electrons was at least 300 keV. This corresponds to a cutoff energy for protons of approximately 240 eV. This electron rejection was checked by using a $^{147}$Pm source having a $\beta^-$ end point energy of 225 keV.
Normally incident particles with this energy were successfully rejected by the magnet configuration.

3. The Geiger Tube

The flux of high energy protons and electrons is measured by an instrument employing a Geiger-Muller counter as its detecting element. The Geiger counter has become a standard detector for high energy particles because of its reliability and simplicity of operation. The Geiger counter used is an EON 6213 end-window tube. The instrument is collimated to a full opening angle of 12.5° and is sensitive to both electrons and protons. The collimation and mounting of the tube are shown in Figure 20.

The minimum energies detectable by the Geiger tube are determined by the thickness of the thin mica window. The window thickness was measured using alpha particles from an Am$^{241}$ source. These particles have an energy of 5.48 MeV corresponding to a range of 4.05 cm in air at STP. The source was kept at a fixed separation distance from the tube and calibrated aluminum absorbers were placed between the source and
the tube. This procedure determined the total absorption necessary so that the alphas could just pass through the mica and be counted. The total thickness of aluminum, air, and mica corresponded to an equivalent range in air of 4.05 atm-cm. Using data on the relative stopping powers of aluminum, air, and mica leads to a window thickness of \( 2.2 \pm 0.2 \text{ mg/cm}^2 \).

The empirical data of Huber (1952) indicates a mica window with such thickness has a transmission coefficient of 50% for electrons of 50 keV energy.

The opening angle of the instrument is defined by aluminum collimators of thickness 0.21 gm/cm\(^2\), corresponding to the range of 600 keV electrons and 12 MeV protons. The full opening angle for the center of the tube window is 12.5°. The maximum angle from the center line visible at the tube window edges is 10°. The effective window area is 0.203 cm\(^2\), leading to a geometric factor of 0.007 cm\(^2\)-ster.

The mica window thickness corresponds to the range of 700 keV protons. Because the energy threshold for protons is so much higher than for electrons and because of the steepness of the auroral spectra, the Geiger tube counting rate will be primarily due to
electrons. For this reason and because the higher energy auroral particles are not quantitatively as significant as the lower energy particles, no effort is made to measure separately the electrons and protons in the higher energy range.

The flux of cosmic rays and other non-auroral particles within the response range of the Geiger tube is estimated to be 10 to 100 cm$^{-2}$ sec$^{-1}$ ster$^{-1}$ (O'Brien, 1964; Cummings et al., 1966), leading to a count rate of 0.07 to 0.7/sec.

After a particle is counted by the tube there is a certain recovery time during which the tube is insensitive to incoming particles. A measurement of this recovery time was made by exposing the Geiger tube to several Pm$^{147}$ beta sources of different intensities. The relative intensities of the sources were determined by measurements at low count rates where dead time losses are unimportant. In this way the observed counting rate can be related to a "true counting rate" which is determined from the relative intensities of the sources. It was found that the true counting rate, $R$, was related to the observed counting rate, $r$, by

$$R = \frac{r}{1 - r\tau}$$

where $\tau$, the effective dead time, equaled 12 $\pm$ 2 $\mu$s.
C. Associated Payload Instrumentation

The output signal from each particle detector amplifier consists of a series of voltage pulses corresponding to the detector counting rate. This pulse rate is converted to an analog voltage signal in the range 0 to 5 volts by a logarithmic count-rate meter (LCRM).

Each input pulse feeds charge into a capacitor in the LCRM until the voltage across the capacitor reaches an equilibrium value. At equilibrium, the rate of loss of charge through the shunt resistor equals the rate of input of the charge by the pulses. The response of the LCRM is logarithmic in that the output voltage is proportional to the log of the input pulse rate. An LCRM calibration curve indicating this behavior is given in Figure 21. Two types of LCRM were used, one having a dynamic range extending up to $10^6$ counts/sec and the other up to $10^5$ counts/sec. The output of each went from 0 to 5 volts.

For single pulses the output of the LCRM is an individual pulse. For multiple input pulses a logarithmically additive pileup occurs leading to a voltage shift in the output level. Input pulses occurring at a uniform rate results in a uniform
FIGURE 21: response of the LCRM as a function of input pulse rate.
output. However, when the input is random then the instantaneous output voltage will deviate from the equilibrium level. Such behavior is illustrated in Figure 22 which was obtained with a random Poissonian input.

The analog output from each of the rate meters and the output from the magnetometer experiment are then transmitted on standard IRIG subcarriers of an FM-FM telemetry system. A simplified block diagram of the payload system is shown in Figure 23.

The configuration of the flight instrument package is shown in Figure 24. The magnetometer is placed at the top of the payload to reduce the effect of stray fields produced by the system electronics. A lunar aspect sensor provides vehicle aspect information for use in reducing the magnetometer vector information. To improve dynamic stability both the fiberglass nosecone and the second stage rocket motor remain attached to the instrumentation package. A door in the side of the payload housing is opened in flight to expose the particle detectors to the aurora.
FIGURE 22

LCRM output for a single input pulse, two closely-spaced pulses, and a Poissonian input from time $T_1$ to $T_3$. Equilibrium is maintained from $T_2$ to $T_3$. 
FIGURE 24: Payload Configuration
The entire payload weight is 58.6 pounds.

The individual payload subsystems were tested at Rice University. Environmental testing of the entire payload system was performed at Goddard Space Flight Center in January, 1969. In late February, 1969, the payload was brought to Fort Churchill, Manitoba, Canada for launch.
III. LAUNCH CONDITIONS AND FLIGHT OPERATION

Churchill Research Range was selected as launch site because of its location in the auroral zone (geomagnetic latitude = 68.7°, L = 8.57), large range impact area (i.e. Hudson Bay) allowing a wide selection of launch azimuths and elevations, and excellent ground support facilities. The latter included radar for payload tracking, telemetry equipment, all-sky camera sites, photometers, and magnetometers. After final payload assembly and checkout were completed the payload was mated to the Nike-Apache launch vehicle. The rocket was then held in launch readiness awaiting the proper auroral conditions.

The general criterion established for launch was the appearance of a bright stable arc beneath the anticipated flight trajectory. A flight azimuth nearest to magnetic north and a low launch elevation angle (78°) had been selected so as to provide a maximum angle between the rocket spin axis and the magnetic field. This would result in greatest pitch angle coverage for the particle detectors. In order to measure the field-aligned current and the particles
it is necessary that the rocket pass over the arc at an altitude of at least 100 km. The nominal locations and times when the payload would be above this altitude were determined from the expected flight trajectory. Using this information the appropriate apparent position or look angles from the Churchill Auroral Observatory were calculated as a guide for deciding to launch.

On the night of February 26, 1969, at about 1940 local time, a bright auroral arc appeared in the northern sky and moved southwards to within range of the rocket. The arc was bright (IBC II), homogeneous with no visible structure near the rocket trajectory, and extended from horizon to horizon in an east-west direction. The decision to launch was made and liftoff occurred at 2004:30 local time. During the flight the arc appearance and brightness remained relatively constant as the arc moved slowly southwards. Figure 25 is an all-sky photograph taken at the time the rocket was over the arc. After the flight, the arc moved overhead, and split into a double structure with many folds and rapid motion. Finally, the arc returned to the
FIGURE 25
All-sky photograph taken at the time the rocket crossed the arc. The zenith is at the intersection of the crosshairs and the location of the rocket is indicated by an arrow. The bright object east of south is the moon.
north and disappeared near the northern horizon about 2030. A small magnetic bay ($\Delta H \sim 50\gamma$) was observed on ground magnetograms coincident with the occurrence of the arc.

Radar tracking showed the rocket performance to be nominal with an apogee of 166 km at 210 seconds into the flight and a total flight time of about 400 seconds. The average horizontal velocity of the rocket was 0.61 km/sec.

After leaving the lower atmosphere, the rocket stabilized with its total angular momentum vector oriented at an angle of 31° with respect to the magnetic field. The rocket spin axis coned about this direction with a coming half angle of 6.6° and a period of approximately 28 seconds. The rocket spin rate was 7.8/sec. These dynamic parameters were determined after launch from the magnetometer and moon sensor data.

Before launch the internal power was activated so that only the magnetometer, transmitter, lunar aspect sensor and solid-state detector were operating.
The instruments requiring high voltage (i.e. the channeltron detectors and Geiger tube) were not functioning at launch. When the rocket reached an altitude of 10,000 feet, a pressure switch initiated a timer. At 49 seconds after launch, the telemetry indicated that the door release mechanism had been activated. At 107 seconds after launch the high voltage to the detectors was turned on. A strong telemetry signal and data from all instruments was received throughout the entire flight.
IV. EXPERIMENTAL RESULTS

A. Data Reduction Method

All instruments functioned satisfactorily throughout the flight although short (~ 5 ms), intermittent (~ 40 per second) interruptions in operation of the detector occurred during portions of the flight. Unfortunately, such times of intermittent detector operation included the period during which the payload was over the arc. For this reason these data interruptions will be examined in detail.

It was anticipated that the flight data would resemble that shown in Figure 22; that is, the rate meters would reach an equilibrium level which would perhaps be modulated at the rocket spin rate if the particle pitch angle distribution were anisotropic. Such an equilibrium level was expected when the payload was over an aurora and lower count rates elsewhere. However, at various times during the flight the flight data appeared dissimilar, as shown in Figure 26. It can be seen that an equilibrium shift was maintained on the electron detector LCRM for a short time until a "dropout" occurred, at which time simultaneous counts were observed from the
FIGURE 26
Example of raw flight data from channeltron detector EP.
channeltron proton detectors and the Geiger tube. Further investigation revealed that large noise spikes on the magnetometer output and false triggering of the lunar aspect sensor also occurred coincident with the dropouts. Such malfunctioning of the lunar aspect sensor and magnetometer did not occur at other times during the flight. This led to the suspicion that the observed behavior was internally generated and was related to payload system operation.

An external source of the erratic behavior was sought and both a highly anisotropic pitch angle distribution and a rocket shadowing of the particle fluxes were evaluated as candidates. A highly anisotropic pitch angle distribution was rejected because the dropouts were not pitch angle correlated. However, the equilibrium levels which were maintained for a short time were found to be part of a modulation envelope at the spin rate and, most importantly, had an amplitude dependence in phase with the pitch angle viewed by the particle detectors. The dropouts were not in phase with the pitch angle, which means that pitch angle data on a single spin is incomplete but complete pitch angle coverage can be obtained by summing over several successive spins. Payload shielding of the particle fluxes is caused by the
helical path of charged particles in the earth's magnetic field. If the pitch of the helix is less than the length of the rocket, the particle may strike the vehicle before it reaches the detector. In our case, it was calculated that payload shielding is possible only for particles with pitch angles in the range 84° to 96°. Since such pitch angles were outside the viewing range of the detector, rocket shielding was rejected as being significant. It should be emphasized that the most serious obstacle to assuming an external cause is the simultaneous effect on all the instruments including the lunar aspect sensor and magnetometer.

The erratic behavior began 1.5 seconds after high voltage turn on, continued almost continuously for the next 30 seconds, and then became less frequent (~ 5% of the total time) for the times near apogee. The data beyond apogee was clean until the rocket reached an altitude of 70 km. whereupon the erratic behavior reappeared and continued for the remaining time of data transmission. Such an altitude dependence is suggestive of a malfunction caused by coronal arcing of the power supplies.

The exact source of the erratic behavior was not determined although a malfunction in the power
distribution system is the prime candidate. The interactions between the payload subsystems are exceedingly complex, and it was decided that pinpointing the exact source would be possible only by constructing a duplicate payload. This would be highly impractical and not justified since future payloads will use a completely different data system.

The interpretation of the erratic behavior shown in Figure 26 is that the particle detectors and LCRM were acting normally in the period AB. Then some malfunction in the payload system (perhaps in the power distribution system) resulted in either removal of the deflection plate voltage on the electrostatic analyzers or the channeltron acceleration voltage. This resulted in the effective turn-off of the instrument until time C when the voltage was restored and the instrument returned to normal operation.

In the analysis of the data only equilibrium periods were assumed to be valid data. Likewise, simultaneous counts on the instruments at low count rates were rejected as spurious. It should be emphasized that as far as could be determined all
instruments performed satisfactorily throughout the flight. The only effect of the intermittent operation of the instruments is that the particle detector data is not continuous. However, it is available from all portions of the flight.

The analysis and reduction of the data was performed manually from an oscillograph of each of the detector outputs. It had originally been intended to digitize this analog output so as to allow a computer reduction of the data. However, the intermittent interruptions in the data required selective analysis which necessitated a manual reduction. A high speed (64 inches per second) oscillograph was made from the flight tape at a time scale 1.6 mm per msec. and an amplitude scale of 40 mm per volt. The amplitude response of the oscillograph was calibrated for non-linearity. The absolute times were determined from a NASA 36-bit time code which had been recorded on the data tape during flight and was printed on the oscillograph with the detector data.
B. General Results and Particle Energy Spectra

The experimental measurements will be summarized in this section and those that follow. These results are based solely on the flight data and do not include the corrections which are discussed in detail in Part V.

Both precipitated and backscattered low energy (2-18 keV) electrons were detected in the portion of the flight later found to correspond with the region of the visible arc. The maximum precipitated electron count rate was about 5,000 counts per second. The count rate due to backscattered electrons was typically about 20% of that measured by the precipitated electron detector.

Electrons with energy greater than 50 keV were not detected conclusively by the Geiger tube in statistically significant quantities. The average count rate throughout the flight was \( \sim 5/\text{sec.} \) with a rate of about 10/sec over the arc. An upper limit to the count rate due to energetic auroral electrons is then 10 counts/sec.

No low energy protons were detected in statistically significant quantities by the channeltron proton detector.
An upper limit to the count rate from these instruments is 10 counts per second, indicating that the proton flux in the energy range 2-18 keV was less than $2 \times 10^{-3}$ times the corresponding electron flux.

Throughout the flight the solid state detector averaged approximately 80 counts/sec. No significant increase (greater than a factor of two) in the counting rate was found in the region of the arc. If the observed counts were due entirely to protons, then the inferred flux would be relatively constant over a broad region ($\sim 120$ km). The observed count rate is considered to be an upper limit to the count rate due to protons since there was no way of determining the background level of the detector in flight.

The particle fluxes inferred from the maximum count rates encountered during flight are shown in Figure 27. Since all instruments measured the integral flux within a wide energy bandpass or greater than the detector threshold, conversion of the data to differential energy spectra requires assumptions as to the form of the incident differential energy spectra. The calculation of a geometric factor integrated over the
Differential energy spectra of maximum fluxes detected in flight. The dotted line is a spectral shape of the form

\[ N(E) = N_0 E^{-1}. \]

The dependence of electron flux on particle pitch angle is shown in Figure 28.
energy bandpass of the channeltron detectors is described in Appendix 1. In Figure 27 the flux of precipitated electrons is shown for both a flat differential spectrum \([N(E) = \text{constant}]\) and an \(E^{-1}\) spectrum \((N(E) = N_0 E^{-1})\), which are characteristic of quiet auroral activity.

The solid state detector is essentially an integral detector measuring the total flux of protons within its bandpass of 80 to 1000 keV. However, the broadness of the lower discriminator level and the steepness of the auroral proton spectrum combine to make it most sensitive to low energy protons.

Assuming an incident proton spectrum of \(N(E) = N_0 E^{-5}\) (Reasoner et al., 1968) and the instrument bandpass shown in Figure 17 results in an effective bandpass of 50 keV to 100 keV with a maximum at 65 keV. In similar fashion, folding the Geiger tube energy response curve into the previously observed auroral electron spectra yields a maximum instrument response for electrons of \(\sim 40\) keV energy. The width of the bandpass is 10 or 20 keV depending on whether the assumed incident spectrum for energies greater than 20 keV is proportional to \(E^{-10}\) (Westerlund, 1969) or \(\exp(-E/10\ \text{keV})\) (Brown, 1966).
The fluxes shown in Figure 27 are those detected at the center of the arc and represent the flux measured at an altitude of about 135 km. A significant conclusion from these measurements is that any localized current composed of particles with energy greater than 2 keV is carried almost entirely by electrons in the energy range 2-18 keV.

In following sections, reference to electrons indicates electrons in the energy range 2 to 18 keV unless otherwise stated.
C. Electron Pitch Angle Distribution

The angular distribution of the particle flux was measured twice per payload spin. The rocket spin axis was aligned at an angle, \( \theta \), with respect to the magnetic field which varied due to vehicle coning from 25° to 37° with a period of approximately 28 seconds. The detectors mounted at an angle, \( \varphi \), with respect to the rocket spin axis viewed a pitch angle, \( \alpha \), given by

\[
\cos \alpha = \cos \varphi \cos \theta + \sin \varphi \sin \theta \cos \omega t,
\]

where \( \omega \) is the rocket spin rate (15.6 \( \pi \) rad/sec) and \( t \) is the time measured from \( \alpha = \alpha_{\text{min}} \). The quantities \( \theta \), \( \omega \), and \( t \) were determined from the magnetometer data with such great precision as to make any uncertainties in the knowledge of \( \alpha \) completely negligible (\( \leq 0.5° \)).

An electron pitch angle distribution is shown in Figure 28 and represents one second of data (a composite of 7 spins) taken at the position over the arc where the maximum fluxes were encountered. The fluxes of precipitated and backscattered electrons were
FIGURE 28: Electron pitch-angle distribution at center of arc where maximum fluxes were detected. Each data point represents the flux occurring in approximately a $4^\circ$ interval centered about the indicated angle.
measured by two separate instruments.

Each data point represents the flux occurring in approximately a $4^\circ$ interval centered about the indicated angle. Representative statistical error bars are shown. The particle flux, $N$, as a function of pitch angle, $\alpha$, has been fit by a least squares method to a linear relation such that

$$N(\alpha) = N_0 + m\alpha$$

For the data shown in Figure 28,

$$N(\alpha) = (3.72 - 0.031\alpha) \times 10^8/cm^2\text{-sec-ster-keV}$$  
$(0 < \alpha < 90^\circ)$

$$N(\alpha) = (1.28 - 0.006\alpha) \times 10^8/cm^2\text{-sec-ster-keV}$$  
$(90 < \alpha < 180^\circ)$

The correlation coefficients for the linear fit are $-0.8$ for the precipitated electrons and $-0.6$ for the backscattered electrons. The statistical probability of such correlation existing between two unrelated variables is less than $10^{-3}$ for both distributions.
A linear fit was used for lack of a more appropriate alternative. The data is also consistent with other relations, such as $N(\alpha) = a + b \cos^n \alpha$. The pitch angle distribution shown in Figure 28 was selected primarily because of the statistical accuracy resulting from the large count rates at the center of the arc. It can be seen that the flux at $80^\circ$ is approximately one-third of the flux at $10^\circ$. A negative slope was a persistent feature of the pitch angle distributions measured during flight. An "average" pitch angle distribution would have the flux at $80^\circ$ equal to approximately 50% of the flux at $10^\circ$. 
D. **Arc Structure**

Since the payload traveled northwards across the arc, the measured electron flux as a function of time indicates the south to north latitudinal intensity profile of the arc. Linear fits of the data within 0.5 second intervals were made by the least squares method and the resulting fluxes at 0° pitch angle are shown in Figure 29.

It may be seen that the total apparent arc width projected on the rocket track is about 8 km. This value does not include corrections for arc motion and the angle between the rocket track and the arc length. These significant corrections are discussed in Part V. The maximum electron fluxes occurred near the center of the arc with a smaller secondary maximum near the north edge of the arc.

Outside the arc no statistically significant fluxes were observed. An upper limit to the electron fluxes in the 2-18 keV energy range is $1.5 \times 10^6 / \text{cm}^2 \cdot \text{sec} \cdot \text{ster} \cdot \text{keV}$. 
FIGURE 29: Half-second samplings of precipitated electron flux linearly extrapolated to zero pitch angle.
E. **Field-Aligned Current Density**

As noted above, electrons were found to be the significant carriers of any energetic (E > 2 keV) particle currents. The measured fluxes are expressed in the form of directional differential intensities. In order to derive a net number flux (current) these fluxes must be integrated over energy and direction (pitch-angle).

The detector response as a function of energy is approximately uniform within the energy bandpass of the detector (see Figure 11). For this reason the number flux of particles within the energy bandpass as inferred from the observed count rate is nearly independent of the energy distribution of the incident particles. This result is discussed in more detail in Appendix 1. For example, the integrated number flux between 2 and 18 keV derived from the measurement by using a flat incident spectrum differs by only 5% from that derived by assuming an $E^{-1}$ spectrum. Calculations of the effect of the nonuniformity of the detector response has been made for various incident differential energy response and are presented in Table 2 following Appendix 1. In the calculations that follow, a flat incident spectrum is assumed. At the
center of the arc the number flux,

\[
J = \int_{18 \text{ keV}}^{2 \text{ keV}} N(E) dE = 6.0 \times 10^9 / \text{cm}^2 \text{-sec-ster}
\]

The average number flux across the arc is \(2 \times 10^9 / \text{cm}^2\text{-sec-ster}\).

No measurement was made of particles with energy less than 2 keV. However, if the fluxes measured between 2 and 18 keV are extrapolated down to 100 eV by an \(E^{-1}\) spectrum, then the number flux will be approximately doubled. If a constant differential energy spectrum is valid, then there will be a negligible increase in the inferred number fluxes by extrapolating below 2 keV.

The electron number flux, \(J\), was measured as a function of pitch angle, \(\alpha\). The net downward electric current, \(J_{||}\), is then given by

\[
J_{||} = \int_{\Omega} neV_{||} d\Omega = \int_{\Omega} J(\alpha) \cos \alpha d\Omega =
\]

\[
2\pi e J(\alpha) \cos \alpha \sin \alpha d\alpha
\]
assuming isotropy in the azimuthal direction about the field line. This assumption is valid because the mean free path is greater than the gyroradius. For a linear pitch angle distribution,

\[ J_\parallel = 2\pi e \int_0^{\pi} (J_0 + m_\alpha) \cos \alpha \sin \alpha d\alpha \]

\[ = \pi e \left[ (J_p^0 + \frac{3}{4} m_p) - (J_b^0 + \frac{3}{4} m_b) \right], \]

where \( J_p, m_p \) and \( J_b, m_b \) indicate the linear fit parameters for the precipitated and backscattered particles, respectively. From the measured data the total net field-aligned current density carried by the particles with energy > 2 keV is calculated to be \( 1.5 \times 10^{-5} \) amp/m\(^2\). This value corresponds to the most intense fluxes observed. The average value of the current density across the arc is \( 5 \times 10^{-6} \) amp/m\(^2\). These values are independent of corrections for arc motion and orientation.

Since the arc length in an east-west direction is much longer than its north-south width, the energetic currents constitute a sheet current. By
numerically integrating the current density across the arc, the equivalent sheet current intensity,

\[ K_{||} = \int_{\text{arc width}} J_{||} \, d\ell, \]

is found to be $5.5 \times 10^3$ amp/m. This value will be corrected for arc motion and orientation in section V below.
V. INTERPRETATION AND APPLICATION OF EXPERIMENTAL RESULTS

A. Atmospheric Effects

The experimental results discussed in the previous section were obtained at an altitude of 130 to 140 km. By the time the particles reach this altitude they have suffered collisions with atmospheric particles. We will now consider the effects that result and any corrections necessary to extrapolate our field-aligned current measurement to higher altitudes.

1. Electron Attenuation and Scattering

An altitude of 135 km \((10^{-2}\text{ mg/cm}^2)\) corresponds to the range of vertically incident electrons with an initial energy of 1.5 keV. Particles with greater initial energy will lose less than 1.5 keV in penetrating to this altitude, as shown in Figure 30. The values in this figure are based on the empirical measurement of the range in air of low-energy electrons by Grün (1957). The net effect of the energy
FIGURE 30

Energy lost by electrons in penetrating from top of the atmosphere to an altitude of 135 km with a constant pitch angle $\alpha$. 
attenuation is that the instrument energy bandpass of 2 to 18 keV actually corresponds to initial energies at the top of the atmosphere of 2.6 to 18.1 keV. Therefore, if the initial differential energy spectrum is flat or proportional to $E^{-1}$, then our measured flux will be smaller by 3% or 11%, respectively. However, differential energy spectra with peaks greater than 3 keV will suffer no relative attenuation in penetrating to this altitude.

Particles with pitch angles greater than zero degrees will lose even more energy since they will have traversed a greater thickness of air. This effect can be estimated by assuming that a particle with pitch angle $\alpha$ has traversed a thickness of air equal to $Z \sec \alpha$ where $Z$ is the atmospheric depth (gm/cm$^2$) at the altitude of measurement. The pitch angle distributions resulting from such a calculation are shown in Figure 3.1. This assumption neglects any change in the particle pitch angle along its dynamic trajectory, which can result from scattering and particle adiabatic motion. The particle adiabatic motion in the converging geomagnetic field is such that $E / B \propto \sin^2 \alpha / B$ is constant. However, in the altitude range where attenuation occurs the field
Pitch-angle distributions observed at 135 km for isotropic angular distributions incident at top of atmosphere. Calculation assumes a measurement of the integral flux of electrons with energy between 2 and 18 keV.
convergence has little effect on the particle motion, as shown in Figure 32. A more serious change in pitch angle results from Coulomb scattering with atmospheric particles. Once a particle has been scattered, all information about its previous motion is lost. However, for the energy range of interest Coulomb scattering is primarily through small angles (Walt et al., 1968; Chappell, 1968). For example, the differential cross section for 10 keV electrons on nitrogen at $5^\circ$ is about 200 times larger than for $40^\circ$ (Chappell, 1968). Also, the particle mean free path at an altitude of 300 km is about 30 km, and at an altitude of 150 km is about 0.5 km. This indicates that a particle will have undergone on the order of $10^2$ collisions before reaching the altitude of measurement, so scattering may seriously alter the electron path through the atmosphere. Using a Monte Carlo method, Maeda (1965) has calculated the atmospheric scattering and energy loss of electrons in the energy range of 2 to 25 keV. The results for vertically and isotropically incident particles indicate that at an altitude of 135 km the angular distribution of electrons with energy greater than about 5 keV will be nearly unchanged from the original distribution. Electrons with energy less than about 3 keV will have lost nearly all resemblance to the original pitch angle
Pitch angle change with altitude assuming adiabatic motion. Dashed line is boundary of nominal loss cone.
distribution. Therefore, without a differential energy measurement no definite conclusions can be reached about the initial angular distribution of the electrons. However, the observed pitch angle distribution does appear to be more similar to that resulting from an initially vertically incident distribution.

If the incident electron angular distribution at the top of the atmosphere was isotropic with a flux equal to that measured at 0° at 135 km, then the total number flux and field aligned current density would be increased by 60%. An initial angular distribution peaked along the field line such that all the particles detected at 135 km were originally distributed uniformly with pitch angles between 0° and 40° would result in a current 90% greater at the top of the atmosphere. The largest increase in the net current would occur if all the particles detected at 135 km were initially vertically incident. In this case the number flux and net current at the top of the atmosphere would be 110% greater than that measured at 135 km. These calculations indicate that the current at the top of the atmosphere is possibly greater by up to 110% than that measured at 135 km. However, we are primarily interested in comparing the auroral particle current with the current deduced by the magnetometer which is insensitive to currents closing
above the altitude of measurement. Therefore, while knowledge of the current density above the altitude of measurement is of interest, it is not essential to the primary goals of this experiment.

The backscattered flux can be examined to determine if it agrees with theoretical precitions. Calculations cited by Cummings et al. (1966) indicate that the ratio of the upward flux with pitch angle \((180^\circ - \alpha)\) to the downward flux at a pitch angle \(\alpha\) will increase as \(\alpha\) approaches \(90^\circ\) and should equal unity at \(\alpha = 90^\circ\). This agrees well with our measured angular distribution. They also compute the total ratio of upward moving particles to downward moving particles to be 0.1 to 0.2. This compares with our observed ratio of 0.21.

2. **Proton Attenuation and Charge-Exchange**

Protons are more seriously affected by atmospheric attenuation than are electrons. The altitude of 135 km corresponds to the range of 2 keV protons.
The most serious correction to the measured proton fluxes are the effects of charge exchange. A fast proton can strip an electron from an atmospheric atom and spend a significant portion of its path through the atmosphere as a fast hydrogen atom. The equilibrium charge exchange ratio \((H^+/H)\) is 11% for 4 keV protons and 30% for 15 keV protons (Nawrocki and Papa, 1963). Charge-exchange equilibrium for 1-20 keV protons is reached at an altitude of 300 km (Eather, 1967). The fast hydrogen atoms will not be counted because they are neutral and will not pass through the electrostatic analyzer. This indicates that the measured fluxes should be multiplied by a factor of 3 to 9 in order to extrapolate to proton flux above the atmosphere.

Another serious effect of charge exchange is that the fast neutral hydrogen atoms are not constrained to follow the field lines in the atmosphere. If a proton spiralling along a field line with an appreciable pitch angle captures an electron at an altitude of several hundred kilometers, it may travel as a neutral hydrogen atom across the field lines for a distance of a hundred or more kilometers (depending on altitude). Davidson (1965) used a Monte Carlo method to compute
the spatial distribution of protons and hydrogen atoms entering the atmosphere with auroral energies. Figure 33 indicates the calculated spreading in a 10 keV beam of protons injected with isotropic pitch angle distribution on an auroral field line. His calculations were for an altitude of 200 km. Below this altitude the mean free path is smaller than the gyroradius, so the particles are unable to move across field lines effectively. Therefore, we are justified in using Davidson's calculations as an indication of the beam spreading at 140 km. A proton beam extending in the latitudinal direction will have a transverse (north-south) spreading profile as shown in Figure 34, where we have simply normalized Davidson's result (Figure 33) and rescaled into more useful units. Normalization is appropriate since the arc was of essentially infinite east-west extent and, therefore, no beam dilution occurs along a line of magnetic latitude. It can be seen that the flux of H+H\textsuperscript{+} along the field line beneath the injection point is diluted by about a factor of 6. Since the charge exchange equilibrium ratio is 11-30\%, the H\textsuperscript{+} flux will be only a factor of 1/18 to 1/60 of the incident flux, depending on energy.

Since the experimental upper limit to the proton fluxes is less than the electron fluxes by a factor of
FIGURE 33

The numbers of protons and hydrogen atoms per cm$^2$ crossing the altitudes of 307 km (dashed line) and 201 km (solid line). An isotropic injection pitch angle distribution was assumed. The proton injection energy is 10 keV; nearly identical results were obtained for 5 and 20 keV. (from Davidson, 1965).
FIGURE 34

North-south proton beam intensity at 140 km relative to beam of unit intensity at top of atmosphere. Spreading is normalized for an arc of infinite east-west extent and a north-south width of 20 km.
500, the charge-exchange corrections do not affect either the identification of the charge carriers or the net current density.

3. **Ionization by Auroral Particles**

The auroral particles are a source of ionization in the upper atmosphere. An energetic particle loses energy at the rate of 35 eV per electron-ion pair; a 3.5 keV electron will create 100 free electrons before it is stopped. We can apply calculations by Rees (1963) to our measured electron fluxes to obtain the altitude profile of ionization production, as shown in Figure 35 where we have assumed an average particle flux of $3 \times 10^9$ electrons/cm$^2$-sec.

An interesting effect results from the fact that ionization equilibrium is not reached instantaneously. The increase in the electron density is given by

$$\frac{dN_e}{dt} = q - \alpha N_e^2,$$

where $q$ is the production rate and $\alpha$ is an effective recombination coefficient. At a time $t$ after the source
FIGURE 35

Ionization production by isotropic streams (0°–80°) of mono-energetic electrons (after Rees, 1963). The ionization production is scaled to an incident flux of $3 \times 10^9 / \text{cm}^2 \cdot \text{sec}$.
has been activated, \( N_e = \sqrt{q/\alpha} \tanh \sqrt{\alpha q} t \), ultimately reaching an equilibrium value of \( N_e = \sqrt{q/\alpha} \). If the ionization source is removed at time \( T \), recovery is given by \( dN_e/dt = -\alpha N_e^2 \), or \( N_e(t) = N_0/(1+\alpha N_0 t) \), where \( N_0 = N(T) = \sqrt{q/\alpha} \tanh \sqrt{\alpha q} T \).

In the height interval between 100 and 140 km, \( \alpha \sim 10^{-7} \text{ cm}^3/\text{sec} \) (Maehlum and O'Brien, 1968). For the inferred production rate of \( q \sim 10^5 \text{ electrons/cm}^3\cdot\text{sec} \), the product \( \sqrt{\alpha q} \) is equal to 0.1/sec. In the typical case where ionization is due to precipitation in a moving arc, the electron density may not reach equilibrium and there will be a "tail" of ionization following the arc. Using arc parameters determined from flight data and ground-based observations, it is estimated that the ionization density beneath the arc attained about 99% of its equilibrium value. This is indicated in Figure 36 for the case of a uniform arc moving at a constant velocity and has been scaled to the measured data.

The above considerations show that the assumption of the electrojet being localized within the arc may not be valid, especially in the case of rapidly-moving bright arcs as are observed in auroral substorms. This effect should be kept in mind when interpreting ground-based magnetograms.
Electron density profile beneath a uniform, 10 km-wide arc moving with velocity $V$. Profile has been scaled to average parameters observed in flight.
4. Pitch Angle Distortion by Currents

The increased ionization resulting from particle precipitation may result in an increase in the horizontal ionospheric currents (auroral electrojet). There is a feedback, however, in that the horizontal currents will distort the geomagnetic field, and, consequently, the particle pitch angle distribution. In a converging magnetic field the particle's adiabatic motion will follow the relation \( \sin^2 \alpha / B = \text{constant} \). The mirror altitude, \( h_m \), at which \( \alpha = 90^\circ \) is determined from \( B(h_m) = B(h_o) / \sin^2 \alpha_o \). If the geomagnetic field is perturbed by currents, then the particles will mirror at an altitude higher or lower than the normal mirror altitude.

The location of the auroral electrojet as deduced from the magnetometer data is shown in Figure 37. The displacement from the location of the precipitated particles is possibly due to the lagging effect discussed in the previous section. The effect of this ionospheric current on the geomagnetic field is indicated in Figure 38 (Park, private communication). The depression in the mirror points for particles mirroring below 135 km is shown in Figure 39. It can be seen that it is significant only for particles
FIGURE 37

Location of the electrojet ($I = 3 \times 10^5$ amp) with respect to the rocket trajectory (dark line) and region of precipitated electrons. Field lines 1 and 2 are 21 and 7 km south of the electrojet, respectively.
FIGURE 38
Change in magnetic field due to electrojet along field lines 1 and 2 in Figure 37. $B_{\text{GEO}}$ is the geomagnetic field and $B_{\text{TOT}}$ is the vector sum of the geomagnetic field and the field due to the electrojet.
FIGURE 39
Depression in mirror altitude, $h_m$, for particles with the indicated pitch angles at 135 km.
with pitch angles between 84° and 88° at 135 km. For this reason, our measurement is unaffected by this result.

The field-aligned currents will have no effect on the particle mirror points since their perturbation on the total magnetic field is only $\sim 0.01 \, \gamma$. 
B. Correlation with Ground-Based Measurements

1. Arc Location and Height

The location and height of the lower border of the arc can be determined by parallactic analysis of all-sky camera photographs taken from separated locations. As long as the lower border is a distinct line in both photographs, this analysis does not require any assumptions about arc height or location. A point on the auroral border as seen from one station corresponds to a direction in space. This direction corresponds to a line in the horizon coordinate system of the second station. The intersection of that line and the auroral border in the second station photograph uniquely determines the location and altitude of the aurora. The procedure used in the reduction of the all-sky camera photographs has been described by Harang (1951) and Brandy and Hill (1964).

Unfortunately, the arc was perversely aligned with respect to the two camera sites so that altitude and location determinations were impossible for the arc portion beneath the flight trajectory. Heights were determined for other points along the arc and found to lie within the range 100 km to 120 km with
an estimated accuracy of \( \pm 15 \) km. This uncertainty was due to arc motion during the two-second photograph exposure time, difficulties in determining the precise lower border of the arc, and orientation of the two stations. Figure 40 indicates the arc position and orientation. Where height-finding analysis was not available, the aurora was assumed to be at an altitude of 110 km. It can be seen that the auroral border and particle precipitation region correspond to within the resolution of the analysis.

The arc position was measured for several times near the period the flight data was obtained. It was estimated that the arc was moving southwards with a velocity along the rocket horizontal track of \( 0.25 \pm 0.1 \) km/sec (R. Park, private communication). The arc motion is important because the spatial dimensions of the arc are inferred from the detector count rate as a function of time. Adding the arc velocity to the rocket horizontal velocity leads to an apparent rocket velocity in the rest frame of the arc of \( 0.86 \pm 0.1 \) km/sec. This results in a 41% increase of the arc dimensions as inferred solely from the flight data (Figure 29).

Another correction to the above measurement is due to the non-perpendicular transit across the arc.
FIGURE 40

Projection of payload trajectory and arc position on horizontal ground plane. Arc position at T + 125 is inferred from analysis of photographs from the Auroral Observatory and Twin Lakes. Also indicated are the meridian of the photometer scan and 100 km points viewed by the Auroral Observatory photometers.
Because the payload traversed the arc slightly obliquely, the inferred path length is actually 8% longer than the true arc width.

2. Auroral Luminosity

The intensity of the auroral emission was measured with 2 sets of photometers. At the Auroral Observatory photometers (2° field of view) were used to look in a fixed direction. This direction was changed during flight so that photometric measurements would be made sequentially of the 100 km entry point, the 100 km point beneath apogee, and the 100 km exit point (see Figure 40). Unfortunately, the southward motion of the arc was such as to bring it between the look angles of the photometer. As a result, only a crude estimate could be obtained of the auroral intensity.

In addition to the Auroral Observatory photometer a meridian scanning photometer was operated by Dr. F. Creutzberg at Fort Churchill. This 2° field-of-view photometer scanned from horizon to horizon along a fixed meridian. Successive scans were made at five
wavelengths. During flight the instruments were run in a fast scan cycle of one second per meridian scan with each complete filter cycle of five wavelengths requiring ten seconds. Successive scans at a particular wavelength resulted in a somewhat variable maximum intensity. This may be due to the arc motion bringing different regions of the arc across the fixed meridian scan. The peak 5577Å intensity varied from 11 kR to 27 kR in the 60-second periods preceding and following rocket traversal of the arc. One kilorayleigh is equal to an apparent emission rate of $10^9$ photons/cm$^2$-(column)-sec. Meridian scans at the 3914 and 5577 wavelengths are shown in Figure 41 for the times nearest to rocket traversal of the arc. The maximum intensities are 6 kR of 3914 and 11 kR of 5577.

These measured auroral luminosities can be used to compare the observed particle fluxes with theoretical estimates of the particle energy deposition necessary to produce such emission. The observed luminosities must first be corrected to an effective emission rate. Corrections for atmospheric extinction and scattering are negligible, amounting to about 10% (Chamberlain, 1961). A more serious correction arises
FIGURE 41: Meridian scan of auroral luminosity at times closest to payload traversal of the arc.
from the finite extent of the arc and the changing path length through the emitting region as the look angle is varied. From a detailed study of such factors Romick and Belon (1967a) concluded that the total number of photons received per second from an auroral arc is not equivalent to, and cannot be used to determine by itself, the integrated emission rate. Extrapolating from their calculations it is estimated that the observed intensities should be increased by a factor of 2 to 5 to obtain an equivalent zenith emission rate.

The maximum particle flux observed over the arc is equivalent to an energy deposition rate of 120 ergs/cm$^2$-sec (assuming an $E^{-1}$ spectrum), with an average energy deposition rate of 34 ergs/cm$^2$-sec. Dalgarno et al. (1965) estimates a conversion relation of 1 kR of 3914 equal to 1.2 ergs/cm$^2$-sec, while O'Brien (1964a) concludes that 1 kR of 5577 is equivalent to 2.8 ergs/cm$^2$-sec. Applying these relations to our uncorrected photometer data yields an equivalent particle energy deposition rate of 7 to 30 ergs/cm$^2$-sec. This is in reasonable agreement with the measured particle energy deposition rate. However, consideration of the experimental and theoretical
uncertainties indicate that this agreement may be reassuring, but is probably not very significant.
C. **Arc Structure**

Having evaluated corrections to the measured values, it is now appropriate to summarize the corrected results.

The corrections to the measured electron fluxes due to atmospheric attenuation and scattering were found to be slight (< 10% at zero pitch angle). Due to the lack of differential energy data, it was not possible to conclusively determine the angular distribution of the electrons at the top of the atmosphere. Therefore, the measured pitch angle distribution will be assumed in the calculation of the number flux and the current density. Also the particle current measured at 135 km is appropriate for comparison with the results of the magnetometer experiment, since the magnetometer is insensitive to currents closing above this altitude. If the measurements in the energy range 2-18 keV are extrapolated down to 100 eV, then the number is either the same or doubled, depending on the assumed differential energy spectrum.

The proton flux at 140 km is severely attenuated due to charge exchange and beam spreading. The maximum combined attenuation due to these two effects results in a reduction in the proton flux at the altitude of measurement to 1/60 of the incident flux at
the top of the atmosphere. Since the measured upper limit to the proton fluxes was 1/500 of the electron fluxes, the conclusion that protons are negligible current carriers is unaltered by atmospheric corrections.

One of the larger corrections to the measured values is due to the arc motion and orientation relative to the rocket trajectory. The combined effect is a 30% increase in the arc size and net sheet current intensity integrated over the arc width. The total sheet current carried by the energetic auroral particles is then 0.07 amp/m, and 0.07 - 0.14 amp/m if extended to lower energy particles. The maximum current density is $1.5 \times 10^{-5}$ amp/m$^2$ with an average value of $5 \times 10^{-6}$ amp/m$^2$. The corrected arc profile is shown in Figure 42.

The measured values can now be compared to previous measurements and models.

The particle fluxes detected over the arc (maximum electron flux of $3 \times 10^8$/cm$^2$-s-sr-keV and an average flux of $10^8$/cm$^2$-s-sr-keV) appear to be typical of previous measurements of auroral particles (Figures 2 and 3).
FIGURE 42: Intensity profile of precipitated electron fluxes. Horizontal scale has been corrected for arc motion and orientation.
The arc width (to 10% point) is about 10 km
with another 3 km-wide secondary maximum to the north
of the primary gaussian-like maximum. Kim and
Volkman (1963) measured the thicknesses of 40
homogeneous auroral arcs using all-sky camera photo-
graphs and found the north-south width ranged between
3.5 to 18.2 km with an average width of 9.1 km.
Maggs and Davis (1968) used an image orthicon TV
system to determine the thicknesses of 581 auroral
structures. The measured widths varied from 70 m
to 4.4 km with a median thickness of only 230 m.
They also note that their measurements may be of
structures within an auroral form since their system
had a low dynamic range. The horizontal intensity
profile of a single auroral arc was determined by
Romick and Belon (1967b) from triangulation of
meridian photometer scans. They found that the hori-
zontal intensity profile could be represented by a
combination of a narrow (~ 10 km wide) gaussian
distribution and a broad (~ 40 km wide) triangular
distribution which had a peak intensity about 1%
that of the gaussian maximum. Our direct measure-
ment of the arc width is consistent with these
previous measurements.
The measured equivalent sheet current of 0.07 to 0.14 amp/m will produce a transverse magnetic field of about 45-90\(\gamma\). Such transverse disturbance magnitudes are typical of those detected by the satellite experiment of Zmuda.

Using the particle detector measurements alone, conclusions can be reached concerning the structure of only the energetic particle currents, since no measurement was made of the low-energy (thermal) particles. The energetic electrons were found to flow in a single region with a spatial extent comparable to arc dimensions. The results then indicate that a current system in which energetic electrons are the current carriers must be localized to within a region of \(\leq 20\) km north-south extent. In addition, the effects of charge exchange and beam spreading indicate that currents localized to auroral arcs or the electrojet cannot be carried in significant quantities by energetic protons. Energetic protons are unable to provide direct charge connection between the electrojet altitude and the outer magnetosphere.

Definitive conclusions can be made about the role of energetic particles in the current system by comparison with the independent current measurement by
the vector magnetometer experiment. The preliminary results indicate an upward current in the region of the downward electron flux with an integrated current density of 0.26 amp/m. This value agrees well with the current density deduced from the auroral particle measurement. Therefore, we can conclude that auroral electrons are significant or possibly total carriers of the upward (downward electron) field aligned current.

The magnetometer experiment also indicates the closing current(s) to be either a single sheet to the south or a single sheet to the south and another to the north of smaller (\(\sim 50\%\)) intensity. The total intensity of the return current(s) is the same as the upward current. Their widths are comparable to that of the downward current and they are immediately adjacent to it. (Park, private communication) Since the measured energetic particle current in these regions is at least a factor of 500 times smaller than the upward return current, it has been determined that the energetic particles are not significant carriers of the closing (downward) currents.

As discussed above, the north-south arc intensity
profile has a double structure with a central primary maximum and a secondary maximum at the northern edge. It was also found that these maxima may correspond to the boundary region or interface between the oppositely directed field-aligned current sheets detected by the magnetometer.

The apparent coincidence between the arc maxima and the current sheet interfaces is suggestive of a energization process or wave-particle interaction at this boundary. For example, a Rayleigh-Taylor plasma instability may result from the magnetic field increase between the oppositely directed current sheets (Jaggi, private communication). It should be noted that the differential current is smaller at the northern interface where the smaller precipitation was found. In addition, the satellite measurements of Zmuda indicate that field-aligned currents are regular (~90%) features of the auroral oval. Since this frequency of occurrence exceeds that of auroral arcs, one is led to the possibility of field-aligned currents carried by low-energy (thermal) particles existing as quasi-permanent features of the auroral oval. An arc would then result from energetic particle precipitation induced by an instability at the
current sheet interface.

This picture of auroral activity is purely speculative and has some immediately apparent difficulties. A major one is that our measurements indicate that the energetic particles are significant carriers of the field-aligned current, which demands a highly efficient energization process. However, these suggestions are offered as encouragement for detailed theoretical examination of plasma-wave instabilities at current sheet interfaces.
D. **Magnetospheric Conditions During Flight**

In order to establish the relevance of our measurement it is necessary to discuss activity elsewhere in the auroral oval and in the magnetosphere.

Figure 43 is a snapshot of the northern hemisphere at the time of our measurement indicating the location of the quiet-time auroral oval. Also shown are the location of all-sky camera stations and the solar terminator. The entire northern auroral oval was in darkness since the solar declination was 9°. It should be noted that Fort Churchill was on the southern edge of the auroral oval.

At the time of flight the arc was also visible at Great Whale River, approximately 1000 km to the southeast of Ft. Churchill (Figure 44). The only other Canadian station from which all-sky photos were available was Tungsten which was in twilight during the time of flight. It can be seen that the arc extended at least 1500 km in an east-west direction including approximately two hours of local time. No substorm characteristics were evident on the all-sky photographs from either station, indicating that the arc studied in our experiment was probably a
FIGURE 43

Location of the auroral oval (shaded region) at time of launch. Local time at Churchill (CH) is 8 P.M. Dashed line is the solar terminator.
FIGURE 44: Arc location at time of launch as seen from Fort Churchill (CH) and Great Whale River (GWR). The dashed line is a line of constant geomagnetic latitude. The dashed circle is the range of view of the all-sky cameras.
classical quiet, pre-breakup arc.

The magnetosphere was disturbed in the 24 hour periods before and after launch. Two solar proton events accompanied by a Forbush decrease had been detected in the 2 days before launch (see Figure 45). The solar wind velocity near the time of launch was also increased above its average value. Geomagnetic activity was enhanced with a storm sudden commencement occurring about 1 hour after flight. As a result of this solar and geomagnetic activity the magnetosphere is compressed and the northern auroral oval moves southward. For this reason Churchill was possibly closer to the center or northern portion of the auroral oval. Except for a bay associated with the occurrence of the arc, no unusual geomagnetic activity was observed at Churchill during the period the arc was visible.

The only other visual auroral activity the night of launch was 3 hours after launch observed at Great Whale River and Churchill and 5 hours after launch observed at Churchill and Tungsten. These events were characterized by arcs and patches and were of short duration (~ 30 minutes).
Solar and geomagnetic activity in late February, 1969. Dashed line indicates flight time of this experiment. Center plot is the flux of solar protons > 10 MeV in units of \( \text{cm}^{-2}\text{sec}\text{-sr}^{-1} \). Previous to this period the average flux had been 0.5/cm\(^2\text{-sec}\text{-sr}^{-1}\). In the ten days prior to this period the solar wind velocity had averaged 350 km/sec.
E. Photoionization as a Source of Auroral Particles

Block and Falthammar (1968) have suggested that photoionization in the high atmosphere may play a significant role in auroral particle precipitation. If there is an electric field parallel to the magnetic field lines driving the field aligned current system, and if there is a potential drop in the topside ionosphere, then ionization produced by solar radiation may be a source for auroral energy particles. They suggest that this may be important not only during the daylight hours but also for the time after sunset when the upper atmosphere is still illuminated by sunlight. Our flight data can provide a useful test of this theory.

Our measurements were made at 8:04 P.M. local time, approximately 2 1/2 hours after local sunset. The sun was 19° below the horizon and the geometrical shadow height was approximately 300 km. Using photoionization data from Nawrocki and Papa (1963) we find that at sunset the height-integrated photoionization between 300 and 400 km is approximately $2 \times 10^9$ ions/cm$^2$-sec. After sunset the solar radiation will not be as intense due to attenuation in passing through the lower atmosphere, but this value is a rough
indication of the total photoionization above 300 km. The average particle flux over the arc was \( \sim 3 \times 10^9/\text{cm}^2\text{-sec} \). It is seen that photoionized particles may be quantitatively sufficient to be of significance. However, if the average electron energy was 4 keV, then an average electric field of 20 mV/m would be required to accelerate photo-produced electrons to this energy if they were produced at an altitude of 350 km. This is a rather large electric field. Also, the apparent auroral luminosity at Great Whale River was similar to that at Churchill. Since the shadow height at Great Whale River was approximately 800 km at this time, it seems difficult to accept photoionization as being significant in auroral particle production.
F. Suggestions for Further Experimentation

The principal limitations to the accuracy of this experiment have been due to the lack of energy spectral information, limited energy range of measurement, and low altitude of the measurement. Obvious improvements would be to use more detectors with narrow energy passbands covering a wider energy range and a launch vehicle capable of reaching a higher altitude. Such a payload is now under construction and is designed to repeat the measurement reported in this thesis with improved accuracy.

Variations on the present experiment could include measurements over a series of multiple arcs to determine the current patterns in this more complicated structure. Also of interest would be measurements at other local times and during substorms, although the current geometries in such cases are not expected to be as simple as for quiet arcs, which would complicate interpretation of the measurements.

An important feature of the present experiment has been the redundant measurement of the current by separate sets of instrumentation. An extension of this approach would be to use other appropriate instrumentation such as electric field measuring
devices and electron density probes.

Certain limitations in the present experiment are inherent in the technique. Since the latitudinal intensity profile was the object of the measurement, a short transit time was unavoidable. If a steeper launch trajectory is used to reduce the horizontal velocity, then temporal variations in auroral activity may become significant. As a result of the short transit time, the statistical accuracy of the measurement is reduced. Another result is that measurements are made only at a single altitude and a narrow latitudinal extent. This eliminates measurement of interesting auroral features which have been previously investigated, such as loss cone diffusion and L-shell dependence of energy spectra. The only way to measure such features with the present experiment would be to use two rockets simultaneously passing over the arc at different altitudes or firing over a series of multiple arcs.

Another possible way to determine the height extent of the observed phenomena is to coordinate the measurement with the overhead passing of a satellite. Unfortunately, the temporal variability of the aurora make such a measurement highly impractical.
It should finally be noted that the success of the present experiment is an indication of the reliability of the technique employed and should serve as an incentive for continued experimental investigation of the relation between field-aligned currents and auroral particles.
VI. SUMMARY AND CONCLUSIONS

A direct measurement was made of the field-aligned current carried by energetic auroral particles in a quiet homogeneous arc. In addition, the south to north intensity profile of the energetic particle fluxes was obtained during the flight across the arc.

Downward electron fluxes (2-18 keV) of about $10^8 \text{ cm}^{-2} \text{sec}^{-1} \text{ster}^{-1} \text{keV}$ were observed with backscattered electron fluxes equal to about 20% of the downward flux. No protons in this energy range or higher energy particles were found in significant quantities.

The energetic particle current measured at the center of the arc at an altitude of 135 km was carried completely by electrons and was found to have a density of $1.5 \times 10^{-5} \text{ amp/m}^2$. Extrapolation of the flux at this altitude to the flux incident at the top of the atmosphere by evaluating the effects of energy attenuation and scattering results in a negligible correction. The angular distribution of the precipitated electrons was anisotropic with the flux at $80^\circ$ equal to 30-50% of the flux at $10^\circ$. A completely isotropic angular distribution would result in a current density 60%
larger than that computed from the observed distribution. Because of the fairly uniform response of the detector within its energy bandpass, the measured current value is relatively insensitive to the form of the incident differential energy spectrum. Extension of the measurement to lower energies by assuming previously observed auroral electron differential energy spectra leads to an estimate of the current carried by auroral electrons with energy $> 100$ eV to be $1.5 - 3.0 \times 10^{-5}$ amp/m$^2$. The current density integrated across the arc width results in an equivalent sheet current intensity of $0.07 - 0.14$ amp/m.

The particle data were compared to preliminary results of an independent measurement of the current system by the vector magnetometer experiment. It was found that the energetic particles carry a substantial portion of the upward current (downward electrons) and are a negligible contribution to the downward current in the field-aligned current system. Arguments based on charge-exchange and beam spreading are made that energetic protons cannot form part of a current system localized to auroral arcs or the electrojet.

The south to north intensity profile was roughly gaussian with a 10% intensity width of 10 km and a
3 km-wide secondary maximum to the north of the primary maximum.

The experimental results were found to be in reasonable agreement with ground-based measurements of the location and intensity of the aurora.

The increased ionization due to the auroral particles was evaluated and it was argued that localization of the ionization (and presumably the electrojet) to the region of particle precipitation does not result for rapidly moving auroras.

The possibility of photoionization being the source of the auroral particles was investigated and rejected.

Examination of all-sky photographs revealed that the arc extended over at least 1500 km in an east-west direction and was not a localized event. No substorm activity was evident and all indications were that the aurora was simply a quiet, pre-breakup arc. This suggests that the measured phenomena may be typical of such auroral activity.
VII. APPENDIX: GEOMETRIC FACTORS AND NUMBER FLUXES

The calibration process involves the determination of the geometric factor as a function of energy, \( G(E) \), such that the incident flux at energy \( E \) is related to the observed count rate \( R \) by

\[
R \text{(counts/sec) = } N \text{(particles/cm}^2\text{-s-ster)} \cdot G \text{(cm}^2\text{-ster}).
\]

For an incident particle flux that is not monoenergetic but has a differential energy spectrum, \( N(E) \), then

\[
R = \int_{E_0}^{E_1} N(E)G(E)\,dE,
\]

where \( E_0 \) and \( E_1 \) are the effective limits to the energy bandpass of the instrument.

In general, the incident spectrum can be expressed in the form \( N(E) = N_0 f(E) \) where \( f(E) \) indicates the relative spectral shape and \( N_0 \) is a scaling factor indicating the intensity of the incident flux. In
such a representation we then have

\[ R = N_0 \int_{E_0}^{E_1} f(E)G(E) \, dE = N_0 \mathcal{N} \]

where \( \mathcal{N} \) (cm\(^2\)-ster-keV) is called the integrated geometric factor. It is apparent that the scaling factor \( N_0 \) inferred from the observed count rate depends on the shape of the incident spectrum.

The total number flux within the bandpass, \( N_T \), is given by

\[ N_T = \int_{E_0}^{E_1} N(E) \, dE = N_0 \int_{E_0}^{E_1} f(E) \, dE = \frac{\int_{E_0}^{E_1} f(E) \, dE}{\int_{E_0}^{E_1} f(E)G(E) \, dE} R = \eta R \]

where \( \eta \) is a number geometric factor and is equal to

\[ \frac{1}{N} \int_{E_0}^{E_1} f(E) \, dE \]

If \( G(E) = G_o \), a constant independent of \( E \), then \( \eta \) is simply equal to \( G_o^{-1} \). As a result, the total
number flux inferred from the observed count rate is independent of \( f(E) \), the shape of the incident spectrum. Tabulation of \( \eta \) for various spectral shapes is given in Table II.
**TABLE 2**

**NUMBER GEOMETRIC FACTORS**

<table>
<thead>
<tr>
<th>Spectral Shape</th>
<th>$\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f(E) = \text{constant}$</td>
<td>1.0</td>
</tr>
<tr>
<td>$f(E) = E^{-1}$</td>
<td>0.96</td>
</tr>
<tr>
<td>$f(E) = \delta(4 \text{ keV})$</td>
<td>0.83</td>
</tr>
<tr>
<td>$f(E) = \delta(6 \text{ keV})$</td>
<td>0.88</td>
</tr>
<tr>
<td>$f(E) = \delta(8 \text{ keV})$</td>
<td>1.18</td>
</tr>
<tr>
<td>$f(E) = \delta(10 \text{ keV})$</td>
<td>1.24</td>
</tr>
</tbody>
</table>

\[ f(E) = \begin{cases} 
\text{constant} & 2 < E < 10 \text{ keV} \\
E^{-5} & 10 < E 
\end{cases} \]

*relative to $f(E) = \text{constant}$
VIII. ACKNOWLEDGEMENTS

It is a pleasure to acknowledge the help and guidance of my thesis advisor, Dr. Hugh R. Anderson. His generous assistance and advice in all phases of this work are sincerely appreciated.

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Finally, it should be noted, in agreement with the findings of Lennon et al. (1967), that you get by with a little help from your friends.
IX. REFERENCES


Park, R. J., Ph.D. Thesis, Rice University, Department of Space Science, 1970.


