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ROCKET-BORNE OBSERVATIONS OF THE

AURORAL ELECTRON ENERGY SPECTRA AND

THEIR PITCH-ANGLE DISTRIBUTION

by

Lawrence Hecker Westerlund

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

DOCTOR OF PHILOSOPHY

Thesis Director's signature:

Houston, Texas

May, 1968
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Introduction</td>
<td>1</td>
</tr>
<tr>
<td>A. Historical Summary of Auroral Physics</td>
<td>2</td>
</tr>
<tr>
<td>B. Recent Measurements of the Auroral Electron Energy Spectra</td>
<td>4</td>
</tr>
<tr>
<td>C. Recent Measurements of the Pitch-Angle Distributions of Auroral Particle Fluxes</td>
<td>10</td>
</tr>
<tr>
<td>D. Transit-Time Studies</td>
<td>13</td>
</tr>
<tr>
<td>E. Purpose of this Investigation</td>
<td>16</td>
</tr>
<tr>
<td>II. Description of the Experiment</td>
<td>20</td>
</tr>
<tr>
<td>A. Data Encoder</td>
<td>24</td>
</tr>
<tr>
<td>B. Detector Complement</td>
<td>31</td>
</tr>
<tr>
<td>C. Measurement of the Separation Velocity and Payload Orientations</td>
<td>47</td>
</tr>
<tr>
<td>D. Environmental Testing and Launch</td>
<td>55</td>
</tr>
<tr>
<td>III. Experimental Results and Analysis</td>
<td>58</td>
</tr>
<tr>
<td>A. Methods of Data Analysis</td>
<td>59</td>
</tr>
<tr>
<td>B. Auroral Electron Energy Spectra</td>
<td>61</td>
</tr>
<tr>
<td>C. Auroral Electron Pitch-Angle Distributions</td>
<td>85</td>
</tr>
<tr>
<td>IV. Conclusions</td>
<td>92</td>
</tr>
<tr>
<td>Figures</td>
<td>97</td>
</tr>
</tbody>
</table>
I. INTRODUCTION

In ancient history, Aurora was the goddess of dawn worshiped by the Greeks. Today, aurora is still admired, studied and occasionally worshiped by present day scientists. The aurora is a complex physical phenomenon resulting from interrelated processes encompassing many facets of magnetospheric and ionospheric physics. It is characterized by luminosities of often complicated and spectacular forms in the night sky at high magnetic latitudes. These forms range from a weak diffuse glow across the sky to a complicated and rapidly changing structure that may be both bright and colorful. The auroral luminosity is caused by the bombardment of the atmosphere by energetic particles, primarily electrons, with the oxygen and nitrogen gases of the upper atmosphere.

The study of aurora may be separated into two nearly separate realms, atmospheric interactions and magnetospheric processes. The first is concerned primarily with the interactions of the charged particles with the atmosphere. The second is the realm with which this work is concerned. Included under the broad heading of magnetospheric processes are a multitude of interdependent phenomena. Here we are concerned primarily with the excitation and transport of the energetic particles into and within the magnetosphere down to the
atmosphere. This includes the processes acting in the solar wind, the shock front, the magnetopause, the tail region and also the magnetosphere itself.

A. HISTORICAL SUMMARY OF AURORAL PHYSICS

The study of aurora has had a long history (cf. Chapman, 1967). The first recorded mention of aurora was by Anazimenes in the sixth century B.C. and later by Aristotle (384-322 B.C.) For 2000 years the aurora was treated in a mystical and superstitious way. It was then discussed in a book of physics by Gassendi (1592-1655) who also gave it the name aurora borealis (northern dawn). Another century passed before Halley (1716) described a great aurora for the Royal Society. From then on the interest in aurora gradually increased. It was found that aurorae were somewhat correlated with sunspots (Halley, 1716), that auroral rays lay along the geomagnetic field lines (Wilcke, 1777), and were located at a height of near 100 km (Cavendish 1790). Captain Cook in 1773 documented the appearance of aurora in the southern hemisphere. However, most of the literature of this time was concerned primarily with the cataloging of particular auroral events rather than the treatment of their causes.

In the 19th century enough data had been accumulated for Muncke (1833) and Loomis (1860) to realize the existence of auroral zones
around the north pole. Late in the century analysis of the auroral optical spectrum was begun. However, only recently have most of the lines and bands been identified.

There have been a great many theories proposed for the aurora. These range from fires at the edge of the earth (Kongespeilet, 1250), to reflection of sunlight off the arctic snow, to the present theory of charged particle bombardment of the atmosphere. Meinel (1950) was the first to obtain experimental proof of charged particle precipitation. He detected the Doppler shifted $H_\alpha$ line in the auroral spectrum which implied energetic protons were being precipitated along the field lines.

Van Allen (1957) made the first direct detection of the auroral particles. While making a latitude survey of primary cosmic radiation, he found "soft radiation" at auroral latitudes. He utilized Geiger tubes carried aloft by rockoons, small rockets launched from balloons. It was demonstrated that this radiation was electrons in the 10-100 kev range and highly variable in intensity. Although the radiation was detected in the auroral zone, the flights were in the daytime and no direct associations with aurora were made.

K. A. Anderson (1960) used scintillation detectors aboard balloons to make the first spectral measurements of auroral X-rays. Then McIlwain (1960) and also Davis et al (1960) made the first direct measurements of the primary particles producing a visible aurora.
They found that most of the luminosity was produced by electrons of less than 10 kev energy. Some protons were detected but of so low an intensity they could produce only a small fraction of the localized auroral luminosity.

With the advent of artificial satellites and the discovery of the Van Allen belts, the intensity of auroral research has greatly increased. Polar orbiting satellites such as the Injun series (O'Brien, 1964 a, b, c) and others have mapped the world-wide morphology of aurorae by direct measurement of both the precipitating particles and the auroral luminosity. It has been found that the aurorae lie at the boundary of trapping in both hemispheres with particles being precipitated at all times. The relation of the particle intensity to auroral luminosity has been investigated along with the particle flux characteristics. These and other investigations will be discussed in detail in the following section.

B. RECENT MEASUREMENTS OF THE AURORAL ELECTRON ENERGY SPECTRA

One of the goals of auroral particle research is the determination of the function

\[ j(E_p, e^{\alpha}, L, B, t) \]

where \( j \) is the directional particle flux, \( E_p \) is the energy of the protons or electrons respectively, \( \alpha \) is the pitch-angle between the particle's
trajectory and the magnetic field direction, \( L \) is the magnetic shell (McIlwain, 1961) on which the particles are located, \( B \) is the magnetic field intensity at the position of the particle, and \( t \) is time (O'Brien, 1965). This function is the fundamental stepping stone to all other areas of auroral research. Knowledge of the precipitating particle parameters is necessary to the study of atmospheric interactions. It is a positive requirement on tests of all theoretical auroral acceleration mechanisms. In addition, study of the function itself may provide insight to the location, size, and characteristics of the auroral source.

At present, the experimental information on \( j (E_e, p, \alpha, L, B, t) \) is abundant in quantity but incomplete. Most experiments to date have measured \( j \) as a function of only one of the parameters, with the others unknown, averaged over or held constant. The various parameters are by no means independent. Consequently the function \( j \) is known only for a few special cases and requires many more experiments of the past type or several more versatile and complete measurements. The purpose of this work is to report one of these more complete measurements, achieved both with improved rocket technology and new and very greatly improved scientific instrumentation.

The present measurements of \( j \) fall into several different categories. Balloon-borne detectors measure primarily the temporal
(t) dependence of \( j \). They are capable of remaining beneath an essentially constant \( B \) and \( L \), and, by indirect measurements via X-rays, determine the magnitude and characteristics of the flux over time intervals from milliseconds to days. However, since these detectors make only indirect measurements, they are incapable of accurately resolving the flux dependence on energy and pitch-angle. On the other hand, rockets and satellites are capable of measuring the particle flux directly to obtain the energy and pitch-angle distributions. However, they lack resolution and accuracy of the other three parameters \( B \), \( L \), and \( t \). Rockets can make measurements for only small intervals of \( B \), \( L \), and \( t \), due to their short time of flight and trajectory. Satellites can make measurements of the particle flux only with rapidly changing values of \( B \) and \( L \) and consequently are unable to distinguish between temporal and spatial effects. They can, however, build up statistical samples of the flux at a particular \( B \) and \( L \) for time intervals on the order of months. Obviously no one experiment can completely define \( j \). Instead, the many measurements must be accumulated and a statistical behavior determined. The following discussion reviews the measurements to date which have shed some light on the characteristics of \( j \).

As mentioned earlier, McIlwain (1960) made one of the first
direct measurements of the auroral particle flux. He launched two rocket payloads, one into a weak diffuse aurora and the other into a bright active auroral arc. In both flights the precipitated flux of protons was found to be relatively quite small, with the ratio of electron to proton flux being of the order 1000 to 1. Scintillation counters were used to obtain the energy spectra of the particle flux. Although the energy resolution of this system was relatively poor, a peak in the electron intensity near 6 kev was detected within the auroral arc. The spectra in the weak diffuse aurora appeared to be exponential, with an e-folding energy of ~5 kev for electrons and ~30 kev for protons. These spectra could be fitted crudely by Maxwell-Boltzman distributions with effective temperatures of $10^7\text{K}$ and $10^8\text{K}$ for electrons and protons respectively. The data indicated that the major portion of the visible auroral luminosity was produced by electrons with energies less than ~10 kev.

Sharp et al. (1965) reported latitude surveys of auroral electrons made on six passes of a satellite through the auroral zone. The data were taken when the atmosphere was illuminated by sunlight. Therefore, no correlations could be made with visible aurora. However, the energy spectra are in qualitative agreement with McIlwain and further the case for his spectra being typical. Sharp extended the energy spectra down to 180 ev., finding a typically flat spectra
from 180 ev to 1 kev. Above 1 kev the spectra monotonically decreased, as did McIlwain's in diffuse aurora. On occasion the spectra remained flat out to 10 kev. These occasions were accompanied by an increase in magnetic activity. Therefore, it might be assumed that the satellite passed through auroral activity containing an electron energy spectra similar to McIlwain's. In addition Sharp found that while the total precipitated energy varied slowly, the higher energy flux (>40 kev) contained very rapid and large variations.

The most extensive previous study of electron spectra has been done by Evans (1966). On two rocket flights into aurora over Ft. Churchill, Manitoba, electron energy spectra were found that were deemed suggestive of an electrostatic acceleration mechanism. On one of the flights into an active aurora a prominent peak at 5.5 kev was found in the spectra. The lack of a high energy tail on both flights tends to rule out theories utilizing plasma instabilities or random processes. In agreement with Sharp's data the higher energy flux contained rapid variations while the lower energy electrons (<10 kev) remained fairly constant. This led Evans to propose the possible existence of two separate acceleration mechanisms for the two energy regions. He suggested an electrostatic field for the lower energy electrons (<10 kev) and a sporadic plasma instability for the higher energy (>10 kev) particles.
Albert (1967) has made a unique measurement of what he calls a "purely mono-energetic beam" of precipitated electrons in the auroral zone. Utilizing a parallel plate electrostatic analyzer and a plastic scintillator, he detected a peak in the spectra near 10 kev (Figure 1). The uniqueness of this measurement lies in the absence of electrons with energies less than 4 kev. Although this absence might be feasible for precipitated electrons at high altitudes it is difficult to justify this absence in the backscattered flux which should certainly contain some secondary low energy electrons. Contrary to the previous experiments, this measurement was not made in an auroral arc, although there was one in the vicinity. In addition the peak linearly increased to higher energies with time. This was attributed to crossing L-shells of monotonically increasing electrostatic potential. Although the uniqueness of these measurements casts a shadow of doubt upon their validity, they none-the-less uphold portions of some auroral theories such as Speiser's (1965) and Bostrom's (1967).

Chase (1967) extended the auroral electron spectra measurements to the day side. His flight into an intense X-ray precipitation event during local morning found a peak in the energy spectra near 2-5 kev. A similarly instrumented payload launched into a quiet auroral arc detected a peak of electrons in the range 5-20 kev. In agreement with Evans, he also found rapid variations in the electron flux greater than
50 kev but very little variation in that less than 20 kev.

The above discussion includes nearly all valid measurement of auroral electron energy spectra to date. There have been many more measurements of electrons in the auroral zone at much higher energies. Since these higher energies (>40 kev) are not important in the production of auroral luminosities and in fact carry a very small fraction of the total energy of the auroral phenomena, they have been left out of this discussion. This is not to imply that the higher energy particles are not part of the auroral phenomena. They are in fact well correlated with aurora and magnetic disturbances. However, the lower energies seem to be more directly responsible for the auroral luminosities and a thorough understanding of these may lead to an understanding of the higher energy particles also.

C. RECENT MEASUREMENTS OF THE PITCH-ANGLE DISTRIBUTIONS OF AURORAL PARTICLE FLUXES

In addition to there being many spectral measurements of greater than 40 kev "auroral" electrons, there have been many pitch-angle studies of these particles also. O'Brien (1964 a, b) made extensive latitude surveys of >40 kev electrons utilizing Geiger tubes aboard Injun 3. Typical pitch-angle distributions are shown in Figure 2. These were normally peaked near 90° with a tendency
to approach isotropy over the upper hemisphere (0-90°) with an increase in flux intensity. When the precipitated flux increased, the backscattered flux, (i.e., those particles being scattered back from the atmosphere) also tended to increase. The backscatter flux was usually ~10% of the precipitated flux as expected on theoretical grounds.

On three rocket flights during auroral conditions, McDiarmid et al. (1967) also measured the pitch-angle distribution of electrons with energies greater than 40 kev. The distribution was found to be a function of the change in intensity of the flux. It became isotropic with an increase in the flux but peaked at 80° during a decrease. Another series of flights (McDiarmid et al., 1964) extended the distributions down to energies of 4 kev. At these lower energies the distributions tended to be more isotropic but still slightly peaked near 90°.

By studying the pitch-angle distribution of auroral zone protons Mozer and Bruston (1966) have postulated that there exists a low altitude electrostatic acceleration process. On a rocket flight into auroral conditions over Iceland, they discovered more protons of 140-250 kev energy moving up the field lines than down. These protons were on trajectories such that they should have mirrored below the atmosphere and thus become absorbed. The detector used
for these measurements had a very large acceptance cone (±22°). Thus the resolution of the distribution was fairly poor. However, the fact of an excess of upward moving protons remains, which apparently could only be explained by an electric field near the top of the atmosphere. The electric field necessary to produce these effects would have to be unreasonably large, on the order of a volt per meter. Such a field would cause drastic effects in the ionosphere and also accelerate electrons into the atmosphere at energies much higher than those observed. Consequently, some other theory needs to be developed to explain these data.

One such theory has been proposed by Cummings et al. (1966) in an attempt to explain anomalously high reflection coefficients of auroral electron fluxes. Both Cummings et al. and McDiarmid et al. (1961) flew Geiger tubes on sounding rockets which measured both the electron influx (precipitated) and outflux (backscattered) simultaneously. Reflection coefficients were obtained as high as 1.2 (outflux/influx), much higher than the expected ten percent. Low altitude electric fields were tried as an explanation of this anomaly but were rejected by Cummings et al. (1966). However, Cummings et al. showed that the effect of ionospheric current systems on the magnetic fields and thus the pitch-angle distributions was sufficient to cause an anomaly in the observed reflection
Although this effect could qualitatively explain the anomalous reflection coefficients, difficulties arose when quantitative agreement was sought with the magnetic distortions observed on the ground. Consequently there has been no satisfactory quantitative explanation for the above data.

In summary, the pitch-angle distribution of auroral particles has been thoroughly investigated for the higher energy electrons (>40 kev) and protons (>140 kev). Except for a few anomalous cases the distributions tend to be peaked at pitch-angles of 90° but approach isotropy over the upper hemisphere when the fluxes intensify with the occurrence of aurora. However, as mentioned previously, it is the lower energy particles which carry the majority of the energy and are of prime importance in the investigation of the auroral phenomena. It is also these same particles which have been investigated the least, primarily because of the technical difficulties involved in their measurement. These are the particles which this work will investigate.

D. TRANSIT-TIME STUDIES

It is now almost generally accepted that the auroral particles were at one time constituents of the solar wind. However, somewhere in their life history they have been accelerated to higher energies before actually reaching the atmosphere and producing aurorae.
This energization mechanism is what has been called the auroral source. As mentioned previously, measurements of the auroral particle parameters such as energy spectra and pitch-angle distributions may lead to an understanding of the energization mechanism. Another parameter which may be placed on the source is the location and physical size of the source region itself. This information would greatly enhance the understanding of the source mechanism by forcing the various auroral theories to meet the boundary conditions in that particular region of space.

Several groups have recently attempted to estimate the location or distance along the magnetic field lines to the source region. This has been done by assuming that any modulation in the auroral electron flux intensity is initiated at the source and is independent of the electron energy. Thus the higher energy electrons will reach the atmosphere before the lower energy electrons. By a close examination of the temporal variations of the electron fluxes at two energies, the time lag, or dispersion, may be determined. This time lag may then be used to predict the location along the magnetic field lines at which the modulation occurred. Using this method Winiecki et al. (1967) and Evans (1967) have placed an upper limit of 1000 km and 2500 km respectively, for the altitude of the modulation source while Bryant et al. (1967) found an altitude of 55,000 km
(i.e. near the geomagnetic equator). Also, Lampton (1967) has found time dispersions in daytime auroral particles which indicate the source to be at 1.5 \( R_e \) or 22 \( R_e \) which corresponds to the ends of the \( L=8 \) field line on which the measurements were performed.

Although these investigators have placed altitudes on the source region, the basic assumptions which they made must be kept in mind. First, the assumption is made that the source mechanism is responsible for the modulation in flux intensity. Second, the dimensions of the source have been assumed to be small with respect to the distance to the source, i.e. it is not an extended source. Third, and most important, they have assumed that the observed modulations are temporal in nature and not spatial.

This last assumption is directly related to another parameter of the source mechanism, i.e. the lateral size of the region. In other words it depends on the distances perpendicular to the magnetic field lines over which coherence of the particle fluxes may be expected. To date, there has been no experimental determination of this coherence size, although it must be at least as large as the gyro-radius of the particles being measured. For a 10 kev electron this amounts to only \(~10\) meters at auroral altitudes of 100 km. Consequently, since even rockets have a horizontal velocity of several tens of m/sec., the time lags which may be validly interpreted as temporal dispersion times are
restricted to a maximum of only a few tenths of a second. A valid measurement of this coherence size is urgently needed not only to supplement the transit-time studies but also as an important parameter of the source region itself. The ideal method of performing this measurement is by the use of two identical payloads which separate horizontally. At some point the coherence of the auroral flux as measured by these payloads will be lost. This horizontal distance is then the coherence size over which any variation in the particle intensity may be assumed to be purely temporal. Although not treated in this thesis, one of the purposes of this research is the measurement of this coherence size and in addition the performance of meaningful transit-time studies.

E. PURPOSE OF THIS INVESTIGATION

In spite of extensive theoretical and experimental investigations, the actual mechanisms which energize and transport the auroral particle fluxes are still unknown. This research will study some of the characteristics of the auroral source through study of the precipitated particles themselves. Among the parameters of the particle fluxes which relate to the source are energy spectra, pitch-angle dependence, coherence size and transit-times of the auroral electrons and protons. The Rice Javelin Twins Rocket program was
conceived to make these studies.

Satellites and, to a lesser extent, sounding rockets cannot easily distinguish between spatial and temporal variations. Since this must be done to measure coherence sizes and transit times, the Twins were designed accordingly. The Twins consisted of two identical payload packages launched together in March 1967 and then separated along the trajectory. The two payloads thus passed through the same points in space but at linearly-varying time intervals. Each payload had six instruments at selected pitch-angles to make many spectral measurements of electrons and protons between ~50 ev and ~100 kev with a time resolution of 10 msecs. By correlating the two sets of data, the spatial and temporal variations can be separated. The coherence size of the fluxes is then easily measured. By correlating the temporal variations of the fluxes in two narrow energy bands with high time resolution, the transit-times of the electrons can be determined. Thereby an estimate for the distance along the field lines to the excitation region may be obtained. This information, combined with the coherence sizes, provides an indication of the physical size and location of the source region, which is highly significant to all theories of the source mechanism. However, because of the exploratory nature of this portion of the experiment, the corresponding
detectors were designed to handle a wide range of flux intensities with good counting statistics. As a result their geometric factors were too large for the actual particle fluxes incurred, causing these particular detectors to saturate periodically throughout the flight. Thus because of the difficulties involved in the analysis of this data, these results have been used instead to greatly refine and improve the scientific detector complement of the second payload of this series to be launched in March, 1968. Definitive studies of the "transit-time" and "coherence sizes" are thus awaiting the launch and analysis of this flight.

Another parameter of the source mechanism will be provided by measurements of auroral particle type, intensity, and energy spectra as a function of pitch angle. When properly weighted by the transport effects along the particle's trajectory, this will provide a direct measurement of the auroral source output. The determination of this source output will provide an immediate test of all theoretical auroral source mechanisms. For instance, a peak in the electron energy spectra would agree with some theories utilizing electric fields or some wave-particle interactions. However, a similar peak in the proton energy spectra would immediately rule out electric fields parallel to the magnetic field.
Similarly energy spectra and pitch-angle distributions of the particles returning from the atmosphere (backscatter particles) will provide clues to the anomalous high reflection coefficients reported by Mozer and Bruston (1966), Cummings et al. (1966) and McDiarmid et al. (1961).

In summary the Javelin Twins have made one of the most complete measurements of the particle flux

\[ j = j(E_p, e, \alpha, L, B, t) \]

as a function of energy, pitch-angle, time and particle type. This information will be used to test theories of the auroral source mechanisms, particle transport, and atmospheric interactions.
II. DESCRIPTION OF THE EXPERIMENT

Several factors were considered in the choice of the rocket vehicle to be used for this experiment. The payload volume had to be large enough to contain two complex instrumentation sections. As much time as possible was needed above the atmosphere and enough height to clear the sensible atmosphere. These requirements dictated a large vehicle. The largest vehicle which can be flown from Fort Churchill is the Javelin, Argo D-4. This vehicle has the capability of carrying a 150 pound payload to altitudes of 800 km with a flight time of 15 minutes. However, in addition to being the most effective available, it also gives the roughest ride with vibration specifications of ±50 g. acceleration. Obviously great care was needed in the mechanical construction of the payload.

The Javelin is a four-stage rocket assembled from one Honest John, two Nikes, and one X-248 rocket motors. The final stage is spin stabilized at a spin rate of nominally nine revolutions per second. Nominal burn-out time of the last stage is 100 seconds after launch. Normal nose cone ejection and payload activation occur 20 seconds later to allow time for the last stage to complete any possible delayed burning. The long range of the Javelin severely restricts the launch azimuth and elevation angles at Fort Churchill.
Therefore, it was necessary to wait for the aurora to reach the proper position rather than aim the rocket at the desired aurora. Fortunately the launch azimuth, though restricted, is in the sometimes favorable direction such that the trajectory is aligned with the usual auroral arc direction.

Three different separation schemes were considered for the Twins. The first consisted of the two sections being thrown off the rocket horizontally by the spin of the rocket itself with the possible assistance of springs. However, it is desirable to have the trajectories of the two payloads in the same plane. The two payloads will then pass through the same point in space at linearly increasing delay times. The spatial and temporal variations can then be unambiguously determined. The possibility of separating the two payloads at precisely the correct point in the spin did not seem to be technically feasible with this scheme. Consequently it was rejected.

Another contemplated scheme consisted of controlling the attitude of the vehicle after burn-out of the last stage and then separating the packages along the desired trajectories. This scheme requires an active attitude control system and was rejected as neither economically nor technically feasible.

The scheme used was a simple ejection or separation along
the trajectory. This satisfied the requirement of separation perpendicular to the magnetic field due to the orientation of the rocket at burn-out being not aligned with $\vec{B}$. The resulting vertical separation was not detrimental since the distances involved were negligible with respect to the motions of the particles coming down the field lines. In addition, the two payload trajectories would automatically lie in the same plane provided that the final coning angle of the vehicle was not large. The past history of the Javelin vehicle indicated that this would not be a problem.

The significant event times in the flight are shown in Table 1. The Twin separation sequence is initiated by nose cone ejection. This event is triggered by two "g-timers" which are started at lift-off of the rocket. The timers were set for 120 seconds at which time an explosive squib pin puller releases the nose cone. As the nose cone left the payload a set of micro-switches initiated the rest of the timers. A three-second timer separated the two Twins from the last stage rocket motor. Two seconds after this event another timer on the last stage released a single 'yo'weight which caused the last stage to enter a tumble. Thus if the last stage incurred any prolonged sporadic burning it had a low probability of catching up and colliding with the Twins. The two Twins then coasted for a period of 25 seconds to allow
TABLE I: EVENT TIMES

<table>
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<th>Event</th>
<th>Time (sec.)</th>
<th>Altitude (km)</th>
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<tbody>
<tr>
<td>1st Stage Ignition</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1st Stage Burnout</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>2nd Stage Ignition</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>2nd Stage Burnout</td>
<td>13</td>
<td>5</td>
</tr>
<tr>
<td>3rd Stage Ignition</td>
<td>25</td>
<td>13</td>
</tr>
<tr>
<td>3rd Stage Burnout</td>
<td>28</td>
<td>16</td>
</tr>
<tr>
<td>4th Stage Ignition</td>
<td>58</td>
<td>50</td>
</tr>
<tr>
<td>Heat Shield Separation</td>
<td>60</td>
<td>52</td>
</tr>
<tr>
<td>4th Stage Burnout</td>
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<td>131</td>
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<tr>
<td>Nose Cone Ejection</td>
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<tr>
<td>4th Stage Separation</td>
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<td>211</td>
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<td>4th Stage Yo Deployed</td>
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<tr>
<td>Twin-Twin Separation</td>
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<td>273</td>
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<td>Twins High Voltage Turn-on</td>
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<td>276</td>
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<td>Apogee</td>
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<tr>
<td>Impact</td>
<td>948</td>
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thorough out-gassing of the payload. This was done in an attempt to avoid high voltage corona when the detectors were turned on. It proved to be a successful technique. At the end of this time the two Twins separated and the detectors were activated. This separation sequence is depicted in Figure 3.

The upper and lower Twin will hereafter be designated as Twin IA and Twin IB respectively. Consequently it is Twin IA which will precede Twin IB through a particular point in space. Thus a spatial structure or variation of the auroral fluxes will be evidenced by its appearance in the Twin IA data first. Twin IB will see this spatial structure a short time later with the lag time being a function of the separation velocity and the velocity of the Twins down range.

All of the basic aspects of the dynamics of the Twins' flight were thoroughly analyzed in the design phase of the program. This analysis, performed by Space Craft, Inc. under the direction of Rice University, indicated that all of the dynamical performance objectives could be met even with a relatively poor performance of the launch vehicle. The most critical dynamical parameter was the coning angle of the Twins before separation. If this angle was large the Twins would be separated in an unpredictable and probably undesirable direction. The dispersion contours of the relative
separation velocity vector perpendicular to the magnetic field are shown in Figure 4 as a function of the final coning angle of the vehicle. In this Figure, $V_\parallel$ is the velocity component parallel to the trajectory plane. The contours represent the maximum velocity achievable for the corresponding coning angle. The actual velocity vector has an equal probability of falling anywhere within the contour. The performance history of the Javelin vehicle indicated that normal coning was less than $3^\circ$, the resolution of the sensors. These predictions were, however, based on obtaining near perfect dynamical balance in each of the flight configurations. This task was well done by the Goddard Space Flight Center facilities. Photographs and drawings of the basic Twins structure are shown in Figures 5-7.

A. DATA ENCODER

The heart of the scientific instrumentation was the data encoder. All the scientific detectors fed their information to the encoder and were in turn commanded to their various modes by the encoder. It is, therefore, necessary to discuss this system before proceeding to the remaining instrumentation.

The encoders used on the Twins are known as Pulse Code Modulation data encoding systems, hereafter referred to as P.C.M.
encoders. These encoders were designed and built by Space Craft, Inc. to Rice specifications. A block diagram of the system is shown in Figure 8. In essence, the P.C.M. encoder generates a twelve-bit digital word for each detector input (both pulse train and analog voltage), and transmits them serially to the telemetry transmitter in a coded pulse train. The bit rate of this output was 22,000 bits per second. Each word contained 12 bits, resulting in a word rate of 1830 words per second. Each frame contained 18 words and therefore, a frame rate of ~100 frames per second was produced. Before describing the assignment of each individual word, the encoding subsystem will be explained.

Each telemetry word is stored or generated in its own register which consists of a series of flip-flops. The data in these registers are in 12-bit binary form. Once each frame these registers are sequentially parallel shifted into a master shift register at the telemetry word rate. The data word bits in the master shift register are then shifted out serially, at the bit rate, into a bi-phase coder. The bi-phase coder converts the binary ones and zeros to a form known as Manchester or split-phase code. This code insures a change in the output level at least once in every bit period. Therefore, the requirement on the telemetry electronics to respond over the complete frequency range from DC (all zeros
or ones) to the bit rate frequency (alternating ones and zeros) is eliminated. The bi-phase data pulse train is then fed directly to the modulation input of the frequency modulation transmitter.

The P.C.M. data format is described in Tables 2 and 3. The first word of each frame is the frame sync word. This word is a twelve bit combination of ones and zeros that appears unchanged in each frame and is the identification of the beginning of each frame. In addition, the frame sync word also identifies the data as belonging to Twin IA or Twin IB since the sync words for the two encoders were different. It is statistically possible that the sync word may occasionally appear elsewhere in the frame. However, this possibility is lessened in the data reduction by requiring the appearance of the next frame sync word eighteen words later, before the individual words are decoded and accepted as good data.

Words 2 and 3a contain the frame counter. The last six most significant bits of this eighteen bit word appear in the first six bits of word three (i.e., 3a). This word contains a binary number which is increased by one each consecutive frame. It is reset to zero when its maximum capacity has been attained. However, this cycle time is approximately thirty minutes compared to a maximum flight time of twenty minutes. Therefore,
<table>
<thead>
<tr>
<th>Word</th>
<th>Assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Frame sync, octal 3107 in Twin IA, octal 7046 in Twin IB</td>
</tr>
<tr>
<td>2</td>
<td>Frame counter</td>
</tr>
<tr>
<td>3a</td>
<td>Six most significant bits of frame counter. (Six most significant bits of word 3.)</td>
</tr>
<tr>
<td>3b</td>
<td>45° magnetometer analog to digital converter (six least significant bits of word 3.)</td>
</tr>
<tr>
<td>4</td>
<td>Downward viewing D.E.D.</td>
</tr>
<tr>
<td>5</td>
<td>Channeltron number 1 of downward viewing SPECS.</td>
</tr>
<tr>
<td>6</td>
<td>Channeltron number 2 of downward viewing SPECS.</td>
</tr>
<tr>
<td>7</td>
<td>Channeltron number 5 of downward viewing SPECS.</td>
</tr>
</tbody>
</table>
| 8    | a. Velocity transducer oscillator (before separation)  
b. Velocity transducer data (at separation)  
c. Subcommutated channeltrons number 3 and 4 of downward viewing SPECS (after separation) |
| 9    | Channeltron number 6 of downward viewing SPECS. |
| 10a  | SPECS high voltage power supply status (six most significant bits of word 10). |
| 10b  | Subcommutated analog to digital converter (see Table 3 for subword format). |
| 11   | Subcommutated channeltrons number 3 and 4 of upward viewing SPECS |
| 12   | Channeltron number 1 of upward viewing SPECS |
Channeltron number 2 of upward viewing SPECS.

Channeltron number 5 of upward viewing SPECS.

Channeltron number 6 of upward viewing SPECS.

High energy upward viewing D.E.D.

Low energy upward viewing D.E.D.

Geiger tube
<table>
<thead>
<tr>
<th>Word</th>
<th>Assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Subcomm sync, octal 77</td>
</tr>
<tr>
<td>2</td>
<td>Battery Pack (VD) voltage monitor</td>
</tr>
<tr>
<td>4</td>
<td>Battery Pack (VN) voltage monitor</td>
</tr>
<tr>
<td>6</td>
<td>Battery Pack Temperature</td>
</tr>
<tr>
<td>8</td>
<td>Power Distribution Box Temperature</td>
</tr>
<tr>
<td>10</td>
<td>Upward viewing SPECS high voltage supply current monitor</td>
</tr>
<tr>
<td>12</td>
<td>Downward viewing SPECS high voltage supply current monitor</td>
</tr>
<tr>
<td>14</td>
<td>P.C.M. Power Supply Temperature</td>
</tr>
<tr>
<td>16</td>
<td>P.C.M. Encoder Temperature</td>
</tr>
<tr>
<td>18</td>
<td>SPECS &quot;drive to zero&quot; indicator</td>
</tr>
</tbody>
</table>
| 20   | a. Velocity transducer rewind signal on Twin IA  
b. Separation indicators on Twin IB |
| 3, 5, 7, 9, 11, | 0° magnetometer |
| 12, 13, 15, 17, 19 | " " |
this word provides a unique identification of each frame throughout the flight.

Word 3b was allotted to the 45° magnetometer. The input to this word contains an analog-to-digital converter. An analog voltage in the range zero to five volts is converted to a six-bit binary number in the range zero to sixty-two. Calibrations show this conversion to be linear within 2%. The output voltage of the 45° magnetometer is thus sampled and telemetered once each frame period.

Words 4 through 9 and 11 through 18 each contains a twelve-bit accumulator. These accumulators accept random pulses from their corresponding scientific detectors and store their sum. Immediately before the previous word has been transmitted out of the encoder, the input to the accumulator of the next word is inhibited and the current number, which is equal to the total number of pulses which had been accumulated in that frame period, is shifted to the master shift register. The accumulator is then reset to zero and allowed to accumulate pulses again for the next frame. Therefore, the binary number transmitted out of the encoder is the total number of counts that were produced in the corresponding detector in the time equal to one frame period.

Each of the detector outputs was fed directly to one of these
accumulators with the exception of words eight and eleven. A Twins detector complement contained sixteen separate detector outputs. However, the P.C.M. encoder was designed to accommodate only fourteen accumulators, a sufficient number for the Twins as they were initially designed. Later the SPECS detectors were improved greatly by the addition of a sixth channeltron thereby necessitating a doubling up or subcommutation of two of the encoder words. This was done on words 8 and 11. These two words had associated with them a reset pulse which was brought out of the encoder and used to synchronize the subcommutation of the two data inputs. This reset pulse drove a subcommutator which switched the input from one channeltron output, to the second, to an open wire (no data) and then back to the first channeltron sequentially. Thus every third frame contained only zeros with the following two frames containing the first and second channeltron data respectively. This use of zeros every third frame was used in the data reduction to identify the two channeltrons. The reset pulse used occurred at the same time that the corresponding accumulator was reset to zero and ready to accumulate data for the next frame. Therefore, mixing of the two channeltron outputs was avoided.
In addition to these two words, word 15 also provided a reset pulse. This pulse also appeared each frame and was used to drive the SPECS high voltage power supply stepping command. These pulses were fed directly to a $2^{10}$ scaler. A tap at the $2^6$ level drove the power supply causing it to step every 64 frames ($\sim 0.64$ seconds). The $2^{10}$ tap drove the "drive to zero" command causing the power supply to supply zero voltage to the deflection plates every 1024 frames ($\sim 10.2$ seconds).

Word 10a, the six most significant bits of word 10, is a parallel entry SPECS status word. These six bits are actually six separate bi-levels. Each bit is controlled separately by the SPECS stepping high voltage supplies. The first three are reserved for the downward viewing SPECS and the last three, the upward viewing SPECS. The six different power supply voltages are indicated in this word by six different combinations of ones and zeros in their corresponding three bits. For example, +35 volts on the deflection plates of the downward viewing SPECS is indicated by a 001 in the first three bits of word 10a, while +350 volts is indicated by 011, etc. Thus the current status of the two high voltage power supplies in SPECS is provided unambiguously every frame.

Word 10b contains the subcommutated analog-to-digital converter. This A-D converter is the same as that used in word 3.
Its input, however, is switched once each frame to one of nineteen separate instrument outputs. Subword 1 is the subcom sync word. This word, always octal 77, uniquely identifies the beginning of each subcommutation cycle. Octal 77 is made unique in this word by the restriction of the analog-to-digital converter output to a maximum value of octal 76. This subcommutated word is decommutated in the same manner as the main data frame. For example if the value of subword 10 is sought, one simply counts nine frames past the frame containing the subcom sync word. Word 10b in this ninth frame then contains subword 10. The next frame contains subword 11, etc. A description of each subword is given in Table 3.

The transmitters used on the Twins were two-watt solid state frequency modulation transmitters, model TR 1125, supplied by Vector, Inc. The P.C.M. encoder output was fed directly to the modulation input of the transmitter. The modulation index of the input signal was adjusted within the P.C.M. encoder to provide approximately 100 kHz telemetry bandwidth but still retain enough power in the center frequency for tracking by the phase-lock receivers. The signal level analysis summarized in Table 4 indicated the use of a two-watt transmitter. The transmitter used produced an actual five watts of output power with a two-watt minimum. Therefore, a large safety factor was introduced by the use
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insertion Loss</td>
<td>5 db</td>
</tr>
<tr>
<td>Polarization Loss</td>
<td>3 db</td>
</tr>
<tr>
<td>Free Space Attenuation (840 km)</td>
<td>139 db</td>
</tr>
<tr>
<td>Receiver Noise Figure</td>
<td>6 db</td>
</tr>
<tr>
<td>Signal to Noise Ratio</td>
<td>13 db</td>
</tr>
<tr>
<td>Transmitting Antenna Gain</td>
<td>( - ) 0 db</td>
</tr>
<tr>
<td>Receiving Antenna Gain</td>
<td>( - ) 16 db</td>
</tr>
<tr>
<td>Noise Density (KTB)</td>
<td>( - ) 174 db/cycle</td>
</tr>
<tr>
<td>Bandwidth (300 kHz)</td>
<td>55 db</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>166 db</strong></td>
</tr>
<tr>
<td>Required Transmitter Power</td>
<td>31 dbm</td>
</tr>
<tr>
<td>Recommended Transmitter Power</td>
<td>33 dbm</td>
</tr>
<tr>
<td>Signal Margin</td>
<td>2 db</td>
</tr>
</tbody>
</table>
of these transmitters.

The antennae for the Twins consisted of phased loop arrays. Each loop in the array was tuned to the operating frequency and had a gap impedance of 100 ohms resistive. The loops were mounted parallel to the payload spin axis, 90° apart, with loops 180° apart phased as a pair. Each pair was then phased with respect to each other and coupled to the transmitter by a power divider. Radiation pattern tests run on the payloads in all flight configurations show the patterns to be nearly omnidirectional. Transmitter frequencies of 248.2 mHz for Twin IA and 244.3 mHz for Twin IB were chosen. The close proximity of these two frequencies allowed the antennae of the two Twins to be physically identical and interchangeable with only minor changes in tuning.

In addition to the telemetry transmitters, a radar beacon was carried in the last stage extension tube. This allowed radar tracking of the entire trajectory (Figure 9) which was beyond the range of the normal skin-track radar.

B. DETECTOR COMPLEMENT

Each of the two Twins carried identical detector complements. These consisted of three types of detectors, including three "D.E.D.s", two "SPECS", and one Geiger tube. The orientations of these
detectors in the payloads are depicted in Figure 10. These detectors will be discussed in detail later, however, a brief summary of their characteristics and the role they played will be given here.

The Geiger tubes are integral energy detectors which measure the electron flux above \( \sim 60 \) kev and the proton flux above \( \sim 1 \) mev. These detectors had a large-area window with a small acceptance cone oriented along the payload spin axis. Two major purposes were served by the inclusion of the Geiger tubes in the detector complement. First, they provided data on the high energy portion of the electron spectrum. Second, they could be used in the transit-time analysis by providing a third set of data for correlation with the D.E.D. data. In addition, the Geiger tubes monitored the high energy background such as cosmic rays and bremsstrahlung which might increase the background in the other detectors.

The SPECS (Switching Proton Electron Channeltron Spectrometer) measured electron and proton fluxes at eighteen different energies. From the SPECS data an eighteen point energy spectrum can be obtained covering energies from 50 ev to 100 kev for both electrons and protons. Each Twin carried two of these devices aligned anti-parallel and at a 45° angle from the payload spin axis. Thus the dependence of these spectra on pitch-angle can be determined. The primary purpose of these detectors was
to provide these spectra for both precipitated and backscattered particles which had not been done previously at these energies.

The D.E.D. (Differential Energy Detector) is a device which measures the electron flux within a single energy passband. It was similar to SPECS in that it used electrostatic deflection to select the electron energy and a Bendix Channeltron Electron Multiplier to detect the electrons. The electro-static deflection system consisted of cylindrical plates which by focusing the electron flux greatly increased the geometric factor. These detectors were aligned parallel to the payload spin axis with two viewing the precipitated electrons and the third viewing downward and detecting the electrons returning from the atmosphere. One of the upward viewing D.E.D.'s was designed to measure electrons of 10 kev energy while the other two detected 5 kev electrons. These detectors were to be used for the determination of the coherence size and transit-time portions of the experiment.

SPECS:

The SPECS instrument (for Switching Proton Electron Channeltron Spectrometer) was developed for measurement of charged particles in space (O'Brien et al. 1967). The device that has made this instrument possible is the channeltron secondary emission multiplier (Evans, 1965). This is a thin tube whose
interior is a secondary-emitting surface. A potential of 3500 volts is established from one end of the tube to the other. When a charged particle strikes the inner surface of the tube at the aperture (where the voltage is at ground potential) secondary electrons are emitted. These are accelerated down the tube and produce further secondary electrons which cascade in turn, so that finally an overall gain of some $10^7$ to $10^8$ is produced. The resultant pulse is collected at the anode and amplified.

In SPECTS, five Bendix Corporation C-shaped channeltrons and one helical "funneltron" are used as depicted in Figure 11. The five C-shaped channeltrons are mounted one on top of the other below the plane of the apertures with the "funneltron" above this plane. The entrance slits provide collimating apertures to define the beam of entering particles. A pair of deflection plates between the aperture and the channeltrons has a voltage $V$ across it. At a given value of $V$, charged particles that enter through the slits will be deflected into one of the six channeltrons if their energies are within the appropriate limits or passbands. If the voltage on the deflection plates is such that electrons are deflected toward the five C-shaped channeltrons, then protons are deflected upwards toward the "funneltron". The locations of the channeltrons are such that an energy range of a decade is sampled in five energy passbands
for a given deflection voltage, and the "funneltron" samples a similar energy range for particles of the opposite charge. The voltage \( V \) is stepped through six voltages \((\pm 35, \pm 350, \pm 3500 \) volts\), giving the passbands shown in Figure 12. The energy spectra of both electrons and protons is thus sampled at 18 points in the range from about 50 ev to 100 kev.

The stepping of the deflection voltage was synchronized to the P.C.M. encoding system to step once each 64 frames. Therefore, each energy interval was sampled and telemetered 64 times before proceeding to the next voltage step. This gave a complete cycle time of 3.8 seconds or .64 seconds for each step. In addition to the six voltage steps, the deflection voltage was driven to zero every 10 seconds for a period of .64 seconds. This was done to measure background counting rates due to ultraviolet light, bremsstrahlung, etc.

Each channeltron of each SPECS was allotted its own P.C.M. telemetry word with the exception of channeltrons three and four. These two channeltrons were subcommutated into a single word due to a shortage of available telemetry words. These two outputs were subcommutated each frame, along with a third "dummy" or zero output. The zero output allowed a means of decommutating the data in this telemetry word by observing the occurrence of the zero output every third frame. The next two frames then contained channeltrons
three and four respectively.

Also allotted to each of the SPECS were three bits of the parallel entry telemetry word. These bits were directly controlled by the logic section of the high voltage power supplies. Thus a unique identification of the deflection plate voltage for each of the six voltage steps was provided. The deflection plate voltage "drive to zero" command was also routed to an analog channel to indicate the times when the deflection plates were at zero voltage.

Detailed calibrations of the energy passbands and angular response of the SPECS were performed in vacuum with beams of electrons of selected energies fired at various angles into the detector. The electron gun and accelerator were designed to provide a uniform electron beam of variable energy over a wide area. To calibrate the angle-dependent energy passbands, the detector was placed in the electron beam and rotated about an axis parallel to the deflection plates. Many measurements were made of the count rate as a function of energy and angle for each channeltron with a particular voltage on the deflection plates. This gave a family of curves for each channeltron (Figure 13), the envelope of which represents the passband of the particular channel for that voltage. These envelopes are plotted for all channels of all four SPECS at 350 V. plate voltage in Figure 14. From these curves the center
energy, full width half maximum points, and the energy portion of
the geometric factor have been calculated. These are shown in
Table 5.

The acceptance angle about the perpendicular plane (i.e. the
angle $\phi$ in Figure 15) was also measured in the electron beam. It is
defined by the width of the collimator slits and the positions of the
channeltrons. The calibrations show this angle to be insensitive to
the particle energy and to be approximately $180^\circ$ full angle for each
of the SPECS.

Ultraviolet contamination was measured in the laboratory
using similar SPECS detectors. These results show the u.v. re-
jection ratio to be on the order of $10^6$. Therefore, during the Twins
flight, which remained in the earth's shadow, the maximum count-
rate due to u.v. contamination from the geocorona would be on the
order of one count per second in the worst case (O'Brien et al. 1967),
well below the actual count-rates (~10,000 cts/sec.) experienced in
this flight.

Furthermore, a negligible upper limit may be placed on the
geocorona u.v. contamination from the flight data alone. Near the
end of the flight the precipitation event suddenly decreased by two
orders of magnitude, and remained at this level for the remainder
(~200 sec.) of the flight. The upwards viewing SPECS was of course
<table>
<thead>
<tr>
<th>Detector**</th>
<th>Channeltron #</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>#1 Center Energy (kev)</td>
<td>.500</td>
<td>.610</td>
<td>.985</td>
<td>1.12</td>
<td>5.50</td>
<td>1.87</td>
</tr>
<tr>
<td>Bandwidth (kev)</td>
<td>.100</td>
<td>.260</td>
<td>.370</td>
<td>.950</td>
<td>6.00</td>
<td>2.06</td>
</tr>
<tr>
<td>EGF*** (kev⁻¹)</td>
<td>14.3</td>
<td>7.15</td>
<td>3.23</td>
<td>1.24</td>
<td>0.22</td>
<td>0.66</td>
</tr>
<tr>
<td>#2 Center Energy (kev)</td>
<td>.470</td>
<td>.640</td>
<td>.935</td>
<td>1.65</td>
<td>4.15</td>
<td>2.76</td>
</tr>
<tr>
<td>Bandwidth (kev)</td>
<td>.100</td>
<td>.160</td>
<td>.330</td>
<td>.900</td>
<td>4.10</td>
<td>3.88</td>
</tr>
<tr>
<td>EGF (kev⁻¹)</td>
<td>12.5</td>
<td>6.66</td>
<td>3.57</td>
<td>1.24</td>
<td>0.29</td>
<td>0.43</td>
</tr>
<tr>
<td>#3 Center Energy (kev)</td>
<td>.485</td>
<td>.625</td>
<td>1.02</td>
<td>1.85</td>
<td>6.66</td>
<td>1.98</td>
</tr>
<tr>
<td>Bandwidth (kev)</td>
<td>.230</td>
<td>.150</td>
<td>.260</td>
<td>1.15</td>
<td>6.50</td>
<td>2.35</td>
</tr>
<tr>
<td>EGF (kev⁻¹)</td>
<td>6.25</td>
<td>10.0</td>
<td>3.80</td>
<td>1.30</td>
<td>0.19</td>
<td>0.83</td>
</tr>
<tr>
<td>#4 Center Energy (kev)</td>
<td>.450</td>
<td>.610</td>
<td>.910</td>
<td>1.57</td>
<td>4.75</td>
<td>2.15</td>
</tr>
<tr>
<td>Bandwidth (kev)</td>
<td>.080</td>
<td>.140</td>
<td>.320</td>
<td>.850</td>
<td>4.50</td>
<td>2.70</td>
</tr>
<tr>
<td>EGF (kev⁻¹)</td>
<td>12.5</td>
<td>10.0</td>
<td>4.00</td>
<td>1.54</td>
<td>232</td>
<td>555</td>
</tr>
</tbody>
</table>

* These passbands correspond to the deflection plate voltage of 350 V. Each of the above values (Center Energy and Bandpass) should be multiplied by a factor of 10⁻¹ and 10⁴ to obtain the values for the deflection plate voltages of 35 V and 3500 V, respectively.

** #1 - Upward viewing Twin IA; #2 - Downward viewing Twin IA; #3 - Upward viewing Twin IB; #4 - Downward viewing Twin IB.

*** Energy Geometric Factor due to bandwidth alone. Uncorrected for efficiencies etc.
still viewing the geocoronal u.v. at this time. Thus even if the false assumption is made that all the counts at this time are due only to u.v. background and no particles whatever, a negligible upper limit of ~100 counts per second is obtained for the worst case, i.e. channel six. Similar arguments may be proposed for the downward viewing SPECS which show that u.v. background from both the geocorona and the aurora itself are negligible (<1%) for all the data to be presented in this study.

The final step in the calibration of all the detectors was to run the entire integrated payload in vacuum with Ni\textsuperscript{63} sources in front of each detector. This was done to obtain relative calibrations between detectors on both Twins and also permitted a final operational check. A Ni\textsuperscript{63} radioactive source was used because its energy spectrum (Figure 16) was similar to that expected to be found in flight. In this section the results of this test will be used only in the sense that they further refined the calibrations of the SPECS detectors.

The electron beam calibrations were considered preliminary or a crude approximation to the actual passbands for many reasons. These are listed below:

1. The number of beam energies used to determine the passbands were restricted by logistics.
2. The contamination from internal scattering into forbidden channeltrons was not thoroughly investigated.

3. The beam was not omnidirectional and therefore all possible incident angles were not included in the calibrations.

4. The calibrations were done primarily with 350 V. on the deflection plates, and also only with electrons. This was a result of limitations on the energy of the electron beam and the lack of a suitable proton beam.

Each of the above areas contributed to second-order uncertainties in the energy passbands of the individual channeltrons. However, these calibrations did give valid results for the center energies of the passbands.

The geometric factors of SPECS include not only areas, solid angles and energy passbands, but also the efficiency of the individual channeltrons. For instance the tolerances in the fabrication of the channeltrons are loose enough to cause appreciable differences in aperture area and position, even though great care was taken to select matched channeltrons for a particular SPECS. In addition, the life histories of the individual channeltrons were not identical, and allowances must be made for varying efficiencies due to contamination within the channeltrons. It was impracticable to measure
each of these variables in the geometric factor for each of the channeltrons.

However, in the actual data reduction we are interested only in the total geometric factor with all these variables combined. To measure this total, the geometric factor was conceptually divided into two parts. The first, or physical geometric factor (PGF), being that due to the effective area and solid angle defined by the entrance apertures of SPECS. The second part, or energy geometric factor (EGF), is that due to the energy passbands, efficiencies, and the above second-order effects. This was done because the physical geometric factor is constant for all of the individual channeltrons while all the variances from channeltron to channeltron will be combined in the energy geometric factor. The calibration or measurement of these two parts was performed as described below.

The energy geometric factor will be described first. The primary contributions to the EGF are the energy passbands as calculated from the electron-beam calibrations. The needed modifications to these numbers can be obtained by exposing SPECS to an omnidirectional electron flux with a spectrum similar to that expected in the aurora. Obviously the ideal method would be to fly SPECS into an aurora with a known energy spectrum. Since this is impossible the next best thing is to place a radioactive source,
with an energy spectrum approximating a possible auroral spectrum, as close to the apertures as possible to provide nearly 180° of isotropy over the entrance apertures. The first iteration to the EGF is then made by adjusting the individual passbands such that the spectrum measured by SPECS agrees with the known spectrum of the source. Call these new geometric factors EGF. These factors then contain the energy passbands, channeltron efficiencies, and second-order scattering within the SPECS housing. Only two more adjustments are necessary, the first involves the background count rate due to ultraviolet light. This previously has been shown to be negligible on the Twins flight. The other background is due to penetrating radiation reaching the channeltrons through the SPECS housing. This is taken account of by a second iteration on the flight data if necessary.

All the backgrounds taken into account, with the exception of u.v., are proportional to the changes in the total electron flux. Therefore, any shifting away from absolute flux levels introduced by these iterations may be corrected by proper measurement of the physical geometric factor. In other words the shape and relative changes observed in the auroral spectra are correct. The only uncertainty introduced by these methods is in the absolute flux level of the spectral curve as a whole. This is corrected by using the final
energy geometric factors when obtaining a physical geometric factor from a known absolute flux incident upon SPECS.

The physical geometric factor is the factor which converts a detector's count rate to particle flux per cm$^2$ steradian. In theory it is simply the product of the effective area and acceptance solid angle of the detector, i.e.

$$\text{PGF} = (\text{eff. area} \times \text{eff. ster.})$$

However, the geometry of SPECS and its electrostatic analyser causes the effective area and acceptance angles to be energy dependent and consequently extremely difficult to calculate. Therefore, the SPECS physical geometric factor was measured experimentally.

This was done by using the Ni$^{63}$ source as a known incident flux. The sources used had been calibrated by their manufacturer in an ion chamber which measures the number of disintegrations per second occurring in the source. The active area of the source was one cm$^2$. For the calibrations, the source was placed within one millimeter of the SPECS apertures. Therefore, it may be assumed that the flux incident upon the apertures of SPECS was isotropic over nearly 180°. If, the total disintegrations per second of the source is $N_o$, the electron flux incident upon SPECS is $N_o$ per $2\pi$ steradians per cm$^2$ per second. Using the energy geometric factors derived above, the energy spectrum of the Ni$^{63}$ source was plotted from the
SPECS count rates. By integrating this spectrum over energy the total number of particles entering SPECS per second can be calculated. Thus the physical geometric factor of SPECS is simply the ratio of the incident flux \( N_o/2\pi \text{particles cm}^{-2} \text{sec}^{-1} \text{ster}^{-1} \) to the integrated count rate of SPECS.

The value of the PGF as derived by this method is \(1.6 \times 10^{-5} \text{ cm}^2 \text{ ster} \). This value differs by a factor of two from that obtained by purely geometric considerations \((.76 \times 10^{-5} \text{ cm}^2 \text{ ster})\). This difference is expected as a result of the methods used to derive the EGF's.

The error bar which needs to be placed on this geometric factor is difficult to arrive at accurately. The main source of error in the physical geometric factor is the uncertainty in the absolute calibrations of the sources themselves. From extensive experience in the handling and the use of these sources it is estimated that the calibration values used are good to within a factor of five. This estimate is partially based on the observed relative differences between the sources as calibrated at Rice and the manufacturer's calibrations. However, as will be seen later, comparison of the SPECS flight data with ground based photometric measurements indicates the geometric factors are correct to within approximately 50\%.
GEIGER TUBE:

Each Twin contained one Geiger tube detector with its acceptance cone oriented along the payload spin axis. Each detector contained an Eon Corporation 8001-T "pancake" type Geiger tube. This tube has a large area window of three square inches with a restraining stainless steel grid over the mica window. This grid is used to prevent the window from blowing out when the tube is placed in vacuum. In keeping with the philosophy of the Twins' detectors, the device is a self contained unit, containing its own high voltage power supply, amplifier, and pulse circuitry. The purpose of using a large area though extremely fragile Geiger tube was to allow the use of a very small acceptance solid angle but still retain a reasonably large geometric factor. The expected small flux of high energy particles could then be measured with statistically significant count rates.

The acceptance solid angle was defined by placing an aluminum honeycomb collimator in front of the Geiger tube. This allowed a small angle collimator with large area to be made in a relatively short length. The resulting acceptance solid-angle had a half angle of \( \sim 10^\circ \) for electrons \(<230 \text{ kev}\). When combined with an effective area of 9 cm\(^2\) the resulting geometric factor is \(0.64 \text{ cm}^2\) steradian. This is a geometric factor several orders of magnitude larger than
the usual satellite and sounding rocket thin-windowed 213 type Geiger tubes.

The true vs. apparent count rate curve was plotted in the usual way utilizing the inverse square law for isotropic flux from a point source. Because of the large dynamic range of the tubes several Pm$^{147}$ beta sources of different intensities were used. The resulting true vs. apparent count rate curves are shown in Figure 17.

The window thicknesses of the tubes were measured using alpha particles from Po$^{210}$. These alpha's have an energy of 5.303 Mev corresponding to a range of $4.5 \times 10^{-3}$ gm/cm$^2$ in air at STP. The count rate vs. distance to the source was plotted, from which the distance was determined at which the alphas could just pass through the mica and be counted. This distance corresponds to a range in air and mica of $4.5 \times 10^{-3}$ gm/cm$^2$. The empirical conversion formula given by Price (1958), converts the range in air equivalent to range in mica. Price's relation is

$$R_m \text{ (mg/cm}^2) = 0.56 R_a \text{ (cm)} A^{1/3}$$

where

$R_m$ = range in mica

$R_a$ = range in air equivalent

$A$ = average atomic weight of mica $\approx 25.2$

$R_a = R - D$
where $R$ is the range of the alpha's in air and $D$ is the distance of the tube from the source. Therefore, in this case

$$R_m \text{ (mg/cm}^2\text{)} = 1.64 (3.3 - D).$$

The window thicknesses of the two tubes flown on the Twins were determined by this method to be $(2.9 \pm 0.7)$ and $(3.1 \pm 0.7)$ mg/cm$^2$ for Twin IA and IB respectively.

The empirical data of O. Huber (1952) indicates a mica window with thickness 3.0 mg/cm$^2$ has a transmission coefficient of 30% for electrons of 60 kev energy. Furthermore, a spare Twins Geiger tube detector, which also had a measured window thickness of 3.0 mg/cm$^2$, was later calibrated in an electron beam. These results also show 30% transmission at 60 kev. Consequently, since the energy response curve rises abruptly to near 100% in this region, the Geiger tube's threshold energy is taken to be 60 kev.

D.E.D.:

Since the D.E.D. data were not used extensively in this work, only a brief description of the device will be given here.

The D.E.D. detectors are single energy passband electron detectors. They used Bendix Channeltron Electron Multipliers as particle sensors and an electrostatic deflection system to focus electrons of a certain energy on the channeltron aperture. A
sectional view of the deflection system is shown in Figure 18. The pulse amplifiers and channeltron high voltage power supplies were identical to those used on SPECS. The calibrations were also performed in the same manner as SPECS. Table 6 summarizes the center energy and passband of each D.E.D. The orientations of these detectors in the Twins payload are depicted in Figure 10.

C. MEASUREMENT OF THE SEPARATION VELOCITY AND PAYLOAD ORIENTATIONS

Knowledge of the Twins relative separation velocity perpendicular to the magnetic field vector is crucial to the analysis of the "transit-time" and "coherence-size" portions of the experiment. This velocity must be known accurately so that the relative positions of the two Twins may be calculated at any time later in the flight. During the design and development phase a large number of different schemes to perform this measurement were analyzed. Among these were Doppler radar instrumentation carried on board, flashing strobe lights observed and recorded from the ground or from the other Twin, and various electrical devices sensing the initial motion of the Twins as they moved apart. Accurate ground based radar tracking of the two Twins was impossible because of insufficient resolution at these slant ranges. After
TABLE 6: ENERGY PASSBANDS OF THE D.E.D. DETECTORS

<table>
<thead>
<tr>
<th>Twin</th>
<th>Detector</th>
<th>$\theta^\circ$</th>
<th>Center Energy (kev)</th>
<th>Bandwidth** (kev)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IA</td>
<td>Hi</td>
<td>$0^\circ$</td>
<td>10.0</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>Lo</td>
<td>$0^\circ$</td>
<td>3.0</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Lo</td>
<td>$180^\circ$</td>
<td>5.5</td>
<td>5</td>
</tr>
<tr>
<td>IB</td>
<td>Hi</td>
<td>$0^\circ$</td>
<td>7.5</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Lo</td>
<td>$0^\circ$</td>
<td>3.5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Lo</td>
<td>$180^\circ$</td>
<td>3.0</td>
<td>6</td>
</tr>
</tbody>
</table>

* Angle between the detectors field of view and the payload spin axis.

** The full width at half maximum value of the detector's electron energy response curve as measured with a variable mono-energetic electron beam.
much deliberation the system described below was finally accepted.

The system used actually consisted of two separate measurements. One was the measurement of the relative separation velocity magnitude. The second was the measurement of the attitude of the payload with respect to the magnetic field vector at the time of separation (Figure 19). The separation velocity component perpendicular to the magnetic field can then be easily calculated from

$$ V = |V| \sin \theta $$

where $\theta$ is the angle between $\vec{V}$ and $\vec{B}$. The velocity measurement will be discussed first.

There were two means of measuring the relative separation velocity of the Twins. The first and primary measurement was to be made by a velocity transducer which directly measured the initial velocity. The second method consisted of accurately calibrating the separation spring and calculating the velocity indirectly using the laws of conservation of energy and momentum.

The velocity transducer is shown in block diagram form in Figure 20. The transducer is actually a mechanical rotary switch attached to Twin IA (upper Twin), and a string that controls the rotary switch attached to Twin IB (lower Twin). As the Twins separated, the string deployed from the transducer causing a string of pulses to be produced by the rotary switch. The time between
pulses was directly proportional to the speed of deployment. At the nominal separation velocity of 10 feet per second the transducer output frequency was 300 pulses per second. The length of the string was such that the pulses lasted for .2 seconds, thus producing approximately 60 pulses of data. The time between pulses was measured by using these pulses to gate a 200 kHz oscillator, and accumulating the number of oscillator pulses appearing within a transducer pulse. To obtain good statistics in the velocity data, the transducer pulse rate was designed to insure at least two or more transducer pulses per telemetry sample period. Logical circuitry was required to select the first full transducer pulse in each frame period for measurement. In addition, the logic circuitry switched the oscillator into P.C.M. word 8 before separation to obtain accurate inflight calibration of the oscillator frequency. At separation the logic switched the transducer electronics to the P.C.M. encoder for velocity data transmission. Immediately after separation the P.C.M. word was returned to its detector for normal use. The signal which transferred the word back to the detector was the turn-on of power to the high voltage supplies of the various detectors. This event was timed to occur one second after separation. Unfortunately, the mechanical shock of the separation "squib" firings jolted the power relays to the "on" position
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The second parameter involved in the calculation of the relative separation velocity perpendicular to $\vec{B}$ is the attitude of the payload with respect to $\vec{B}$ at the time of separation. This angle was measured by means of the magnetometers carried on board the Twins. Each payload contained two Schoenstedt Ram 5C magnetometers. This device is a single component magnetometer having a range of $\pm 600$ mgauss. It provides an output voltage proportional to the magnetic field component parallel to the axis of its sensor,

$$V_o \propto |B| \cos \theta$$

where $V_o$ is the output voltage; $B$, the magnitude of the magnetic field, and $\theta$, the angle between $\vec{B}$ and the magnetometer probe axis. One of these magnetometers was oriented parallel to the spin axis and the other at a $45^\circ$ angle to the spin axis and parallel to the SPECS detectors. Consequently, the magnetometer parallel to the spin axis would measure the angle with respect to the magnetic field and also any coning angle which might be present. However, this required the knowledge of the magnitude of the magnetic field at the payload and accurate absolute calibrations of the magnetometer. It was discovered in the field that the explosive squibs had an unexpected magnetization which biased the magnetometers away from their absolute calibrations. Therefore, another method
was needed to obtain the attitude of the payloads.

Although the angle $\theta$ between the payload spin axis and the B field cannot be measured directly because of the unknown bias, it may be deduced from the 45$^\circ$ magnetometer data. This magnetometer produces a sine wave with a frequency equal to the spin rate of the payload and a magnitude which is related to the angle $\theta$. The magnitudes of the maximum and minimum of this wave are ambiguous due to the biasing. However, the relative difference, or peak to peak change, can be related to $\theta$ by the existing calibrations.

The magnetometers were calibrated at Rice both inside and outside the payload to allow for any inherent magnetization of the payload itself. First their response to known magnetic fields was measured by placing them in a calibration coil through which a measured current was passed. The earth's field was excluded by wrapping the coils in mu-metal. The results of this calibration show their response to be linear with magnetic field. The final calibration was performed in the integrated payload (with the exception of live explosive squibs) by changing the attitude of the entire payload with respect to the earth's field. From these data a plot of magnetic field versus telemetry output of the magnetometer channel was made as shown in Figure 21. As a result of the
attitude agrees with the predicted change of approximately 20°. A change of 40° would be required to cause θ to be greater than 45°. A change of this magnitude would be accompanied by a large coning angle which was not detected.

Combining the above equations, we obtain,

\[
\frac{\Delta B}{B_C} = \cos (\Theta + 45°) - \cos (45° - \Theta)
\]

\[
= -2 \sin \frac{1}{2} (90°) \sin \frac{1}{2} (2\Theta)
\]

\[
= -2 \sin (45°) \sin \Theta
\]

and thus

\[
\Theta = \sin^{-1} \left( \frac{\Delta B}{\sqrt{2} B_C} \right)
\]

The magnetic field at the point of separation (273 km altitude) over Fort Churchill has been calculated to be 538 mgauss. Immediately after separation, ΔB from Twin IA is -320 mgauss while Twin IB indicates -335 mgauss. Therefore,

\[
\Theta_{Twin \ IA} = 24.8°
\]

\[
\Theta_{Twin \ IB} = 26.0°
\]

Physically θ for each Twin must be identical. The above difference is presumably due to calibration error, tolerances in alignment of the probes and quantization resolution of the magnetometer signals. Therefore, the average θ of 25.4° is taken to be the angle of the payload spin axis to the magnetic field. It is noted here also that if the payload field is neglected and a straightforward measurement
of $\theta$ is made using the 45° magnetometer calibration data, a result of 23° is arrived at. Thus, after the squibs had been detonated their magnetization was reduced to a level which caused only a 2° deviation from the pre-launch calibrations.

It was shown earlier that the relative separation velocity of the Twins is 2.64 meters per second. Therefore, the relative velocity of the Twins perpendicular to the magnetic field is

$$V_L = V_S \sin 25° = 1.11 \pm 0.06 \text{ m/sec}.$$  

D. ENVIRONMENTAL TESTING AND LAUNCH

In addition to the calibration of the individual detectors, each subsystem and detector was subjected to environmental testing, both separately and in the integrated payload. The Javelin rocket provides an extremely rough vibration environment. With this in mind, all detectors and systems were designed and working prototypes built as early in the program as possible. An operational prototype Twin and a mechanically equivalent mock-up Twin were then built and taken to Goddard Space Flight Center for environmental and separation tests. These tests included static and dynamic balance, vibration, and separation in vacuum. The balancing was done to determine if the desired balance specifications for each flight configuration could be met with the present design.
They were also necessary for conducting meaningful separation tests in vacuum while the payload was spinning at the rate expected during flight. Individual moments of inertia and center of gravity measurements were also made so that revision of flight dynamics and trajectory calculations could be performed.

The payload was then transferred to the large vacuum system for tests of the three separation events. For each test the vacuum chamber was evacuated to 10 mm. Hg, the payload spun up and the separation event initiated. The separated portion of the payload was caught and suspended from a long cable attached to a counter-weight. High speed motion picture coverage was used to study the events. Each separation occurred as predicted with no evidence of "tip-off" or malfunction.

Vibration tests in each axis were then performed on the payload as a whole. Accelerometers were placed at critical points in the payload and did not indicate any excessive vibration amplification. No major failures or design problems were incurred in any of the above tests.

Following integration of the completed flight payload, additional operational and environmental tests were performed. These included operational and reliability checks of the separation sequence, magnetometer calibrations, and complete systems operation in
vacuum. Final static and dynamic balance were performed at Goddard Space Flight Center in addition to flight qualification vibration tests.

The launch team and payload arrived at Fort Churchill on 3 February 1967. The payload was prepared for launch and mated to the rocket vehicle. By 23 February the rocket had not been launched due to inclement weather and lack of suitable auroral conditions. New moon had occurred on the ninth of the month and by this time the moon was hindering observation of aurora. Also, other groups were awaiting the use of the range. At this time it was decided to postpone the launch until the following month. Upon return to Fort Churchill the payload was again prepared for launch and returned to the launcher by 8 March. Again weather conditions, range safety and lack of suitable auroral conditions delayed the launch until the night of 17 March 1967.
III. EXPERIMENTAL RESULTS AND ANALYSIS

The Twins were launched on 18 March 1967, at 05:47 G.M.T. (23:47 local time) from Fort Churchill, Canada, Lat. 58°44'N. (69° magnetic latitude, L=8.7), Long. 93°49'W. The auroral conditions at the time were a general diffuse glow across the sky of about 5 kR of 3914 Å with a strong arc in the north moving slowly towards the south. This arc had a peak luminosity of more than 25 kR of 3914 Å at the time of crossing the rocket trajectory (Figure 23).

The Fort Churchill magnetometer records show auroral activity beginning about an hour before launch with a maximum excursion in all three axes of ~100 gammas near the time of launch. The records during the flight are typified by a gradual recovery to quiet conditions. The Y-axis (East-West) fluxgate magnetometer shows more activity than the X-axis or north-south direction. This is in general agreement with the auroral arc orientation which lay in a more nearly north-south direction.

The riometer (30 mHz.) records show essentially no activity throughout the night with the exception of a 1 db spike at the time the arc passed overhead.

The trajectory of the rocket was near nominal with a flight azimuth of 51° which placed the trajectory nearly perpendicular to
the orientation of the arc. A total flight time of 940 seconds was achieved, producing more than 700 seconds of useful data. The payloads reached a peak altitude of 794 km and an impact range of 516 km giving a horizontal velocity of 0.545 km/sec, downrange (Figure 9).

All systems on board worked perfectly throughout the flight, with the exception of the loss of the velocity transducer data (described above) and one of the Geiger tubes which did not survive the launch. As an indication of the very large amount of data received, a total of 3.38 million separate measurements were made. Obviously the best way to analyze this amount of data is with a digital computer.

A. METHODS OF DATA ANALYSIS

The telemetry signals from the two Twins were received by two redundant antennae and receivers. The R.F. video signals were recorded on redundant magnetic tape recorders along with an IRIG binary-coded-decimal (BCD) time code. This data tape was read by the Rice SDS 92 computer which broke the serial P.C.M. bit train into the corresponding twelve-bit words and rewrote the tape in an IBM computer format. The data were broken up into records each containing a nominal 100 P.C.M. frames (~1 second of data). Each record also contained the real time (~1 millisec.) at which the first word of that
record was received. The data from the two Twins were packed in two separate files with the time information being the parameter used for temporal comparison of the two sets of data. Tape reading subroutines were written for the Rice IBM 7040 computer which would read this tape. These routines read the tape, word by word, searching for the proper P.C.M. sync word. When one was found, the computer looked for another sync word eighteen words further on in the data. If this second sync word was found, the intervening P.C.M. frame was accepted as good data, broken up into the corresponding words, and made available for computation. Included in this routine was the capability of positioning the data tape to the desired portion of data by supplying the desired record number or frame counter number. The data were then called up for computation one frame at a time, consecutively. Most of the computations involved averaging and sorting the data according to pitch-angle, SPECS high voltage status, etc. The output was usually in the form of a large array of numbers. To enhance the possibility of studying a large portion of the tremendous amount of data, generalized plotting routines were developed for the Rice Calcomp digital plotter. These routines provided the welcome capability of analyzing extremely large numbers of data points, displayed in several forms, without the time-consuming task of hand plotting each individual point. Thus the Twins data-reduction processing combined the
advantages of a visual display analog system with the resolution of a digital system when needed.

B. AURORAL ELECTRON ENERGY SPECTRA

The particle energy spectra data presented here were taken from the two "SPECS" on board Twin IB. The SPECS on Twin IA were used primarily as a check on these results. This choice was largely arbitrary but was prompted by the lack of data from two channeltrons in Twin IA. This loss was a result of the failure of the transducer electronics to return its data channel to channeltrons three and four of the downward viewing SPECS after separation.

The spectra were reconstructed from the raw data by extensive use of the Rice IBM 7040 computer. Programs were written for this computer which could decode the SPECS power supply status indicators and accumulate the channeltron data until the power supply switched to a new deflection-plate voltage. The subcommutated channeltrons, three and four, were then identified and separated before averages of all channeltrons for that particular time interval were calculated. After the data had been accumulated in this manner for one complete power supply switching cycle, the individual spectral points were multiplied by their corresponding geometric factors and a plot of particle flux versus energy generated by the Calcomp plotter routines.
calculated without taking into account the physical geometric factor, i.e. effective area and subtended solid angle. This factor has not yet been definitively measured but may be estimated to be near $10^{5.25}$ as shown previously. Thus to obtain the particle flux in terms of particles cm$^{-2}$ sec$^{-1}$ ster$^{-1}$ kev$^{-1}$, the flux values shown should be increased by a factor of approximately $10^5$. These spectra are averaged over pitch-angles from 20° to 70° in the upper hemisphere. The payloads were spinning at ~9 revolutions per second. Thus since each point in the spectra was obtained in a time interval of 0.5 seconds, it represents approximately five cycles through the pitch-angle distribution.

Unfortunately the proton flux levels during the flight were well below the limit of detectability of the SPECS detector. The calibrations of these detectors with the Ni$^{63}$ sources indicated that internal scattering of electrons within the SPECS front-end housing was sufficient to cause an appreciable background count-rate. The Ni$^{63}$ sources produce electrons exclusively. The background count-rate was thus calculated by comparing the "proton" count-rate of each channeltron at each deflection plate voltage with the corresponding Ni$^{63}$ electron count-rates. These ratios varied from channel to channel but were typically on the order of 10% of the electron flux. The ratios were found to be essentially independent of the detector used and also independent of the electron flux.
level, i.e. the background is proportional (~10%) to the electron flux.

This contamination is taken into account by the procedures used in the calibrations for electrons. However, it does set a lower limit on the proton flux detectable by SPECS. The "proton" data observed in the Twins flight can be contributed almost entirely to this contamination. Furthermore, the proton fluxes which can be predicted (Reasoner et al. 1968) from the $H_\alpha$ intensity of 10-20R observed through the flight are an order of magnitude below the "proton" fluxes observed by SPECS. It is impossible to retrieve the real proton fluxes from this data because of the large uncertainties in the background flux coupled with a "signal-to-noise" ratio of less than 1:10.

The electron spectra shown in Figure 24 were taken from periods in the flight characterized by low and fairly constant flux levels in all detectors on board. These times have been correlated with the all-sky camera photographs which typically show a lack of bright auroral luminosities at the 100 km level below the payload. However, as noted previously, the ground photometers never saw less than ~5 kR of 3914 Å below the payloads throughout the flight. Therefore, these spectra might be said to be typical of a mantle or weak diffuse, aurora.

If these spectra were characterized by a power law,

$$N(E) = N_0 E^\gamma, \ (0.1 \text{ kev}<E<10 \text{ kev})$$
the exponent would be approximately \(-1.3 \pm 0.3\) for the energies
between 100 ev and 10 kev. This slope of the spectrum remains
fairly constant for the entire flight. Because of the continuous
presence of this characteristic spectrum throughout the flight, it
will be called the continuum hereafter in order to distinguish be-
tween it and the spectrum associated with the auroral arcs.

Another important feature of these spectra is the gradual
decrease of flux in the lowest energy channels. Several explana-
tions might be offered to explain this feature. Among them is the
possibility that the channeltron efficiencies might be decaying with
time. This effect has been observed in the laboratory. Immediately
after turn on of a channeltron, its efficiency decays exponentially with
a time constant of approximately five minutes. The effect is not a
function of the particle energy or type, and is also seen when ultra-
violet photons are activating the channeltron (J. Burch, private com-
munication). In the Twins data, however, the decrease in channel-
trons 1 and 2 occurs for times of up to ten minutes. The efficiencies
of channeltrons 1 and 2 at the other five deflection plate voltages do
not seem to be affected. Furthermore, the effect is duplicated in the
data from the other Twin. The possibility of electro-static charge
build-up within SPECS occurring in the same way in the two upward
viewing SPECS but not in the two downward viewing SPECS is
extremely remote. Consequently the effect does not appear to be instrumental, but is instead a characteristic of the auroral particles themselves.

The next explanation which comes to mind is an altitude effect. In other words at lower altitudes more low energy secondary electrons are seen. However, this is definitely not the case since the effect continues monotonically into the down leg of the flight as long as the precipitation persists.

Therefore, for the lack of any other explanation, we are left with only two possible interpretations for this effect. First, we might assume that the entire energy spectrum has gradually shifted to higher energies, i.e. an energization process. This energization may be a function of time, latitude, longitude, or a combination of these. Second, it might be assumed that the effect is due to some type of selection mechanism. In other words, the particles must possess a progressively increasing minimum energy in order to appear on these field lines. Again this selection process may also be a function of time, latitude, and/or longitude. Before discussing these processes further, the original source of this particle flux must be investigated.

One method of determining the source of auroral fluxes is to measure the relative populations of the various constituents and comparing these to other regions where the populations are known.
Reasoner et al. (1968) have found that the ratio of proton to alpha particles (>100 kev) in a nighttime aurora is the same, within statistical limits, as that measured nearly simultaneously in the solar wind. This ratio in the thermal plasma within the inner magnetosphere below an altitude of ~20,000 km differs by a factor of ~100. Consequently they propose that the auroral particle fluxes were originally part of the solar wind and not trapped radiation that has been stored in the magnetosphere before being precipitated.

Another indication of the original source of a particle flux such as this may be obtained by comparing the energy spectrum with spectra measured in other regions of space. O'Brien (1966) has reviewed the many different magnetospheric regions and the characteristics of the particle fluxes which populate them. He has shown that all the various regions of the magnetosphere and its environs may be classified in only four domains according to the characteristics of the particle fluxes. The electron energy spectra of these four domains are sketched in Figure 26. Although this figure was intended to be simply a sketch which attempted to bracket all previous experimental measurements, it still represents a reasonable compilation of all measurements to date, i.e. two years later. The continuum spectrum observed by the Twins fits most readily into the domain of thermalized solar wind. This domain is characterized by a proton energy spectrum which is
peaked near 100 ev and contains a non-thermal high energy tail (Gosling et al., 1967). Michel (1967) has shown that the unexpected high energy tail may indeed be present in a post-shock plasma which contains temperature inhomogeneities such as the solar wind. He has also demonstrated (Michel, 1965) that the electron component of the thermalized solar wind should have approximately the same temperature as that of the ions, i.e. \(~100\) ev.

Both Frank (1967) on OGO 3 and Bame et al. (1967) with the Vela series, have flown detectors on satellites which have traversed the magnetosheath and measured these electron energy spectra. A portion of Frank's data is reproduced in Figure 27. Though his data extends down to energies of only 100 ev, there is a definite indication that a peak may exist at \(~100\) ev or at least that most of the particles have energies \(~100\) ev.

As mentioned earlier the Twins spectra fit most readily into the domain of the thermalized solar wind inhabiting the magnetosheath. The spectra contain a peak at \(~100\) ev similar to the thermalized solar wind. In addition the slope of the spectra agrees fairly well with that observed by Frank (Figure 27) in the magnetosheath. If Frank's spectrum is fitted by a power law, the exponent would be approximately (-2), while the Twins data may be fitted with an exponent of \((-1.3 \pm 0.3)\). Furthermore, Reasoner et al. (1968) have shown the proton to alpha
ratio in the auroral flux to be the same as that in the solar wind and hence presumably the thermalized solar wind also. Consequently, it might be assumed that the continuum electron fluxes observed by the Twins are actually thermalized solar wind particles that have undergone little or no changes in energy during their transport to auroral altitudes.

A stronger case may be made for the plasma sheet of the magnetotail as the source of these continuum particles. The electron energy spectra in this region has been measured by Montgomery (1968) using the Vela Launch 2 satellites. His data, shown in Figure 28, show a striking similarity to the spectra obtained by the Twins. In this case also, the peak near 100 ev, comparable fluxes and similar, though somewhat steeper, slopes tend to argue that the particles seen by Montgomery could possibly be the source of those measured at auroral altitudes by the Twins. This analogy is made even stronger by the appearance of a second peak in Montgomery's spectra near 10 kev similar to the Twins' spectra shown in Figure 25. Montgomery's data was obtained on the midnight to dawn side of the earth when the Vela satellite was at a distance of 17 R_E, i.e. in the plasma sheet of the magnetotail. This is in the vicinity of the tail where the auroral zone field lines would be if they were open and extended into the tail. Consequently this data provides a promising but not conclusive indication that
the auroral zone field lines extend back into the tail, thereby allowing
the plasma sheet electrons direct access to auroral altitudes.

Returning now to the gradual shift to higher energies of the
continuum spectrum, static electric fields are immediately brought
to mind as a possible cause. If we assume the shift to be a function
of latitude, or in other words a crossing of L-shells to the north, then
the electric field at 100 km altitude necessary to produce this effect
would be of the order 0.3 volts/km directed toward the equator.
Normally, L-shells are assumed to be equipotentials. Therefore, an
electric field such as proposed here may be mapped along the field
lines to higher altitudes. A maximum shift of 100 volts is seen in
the energy spectra as the Twins moved from an L-shell of 9 to approx-
imately 12. Consequently, if this shift is indeed due to electric fields
perpendicular to the magnetic field, the required magnitude would be a
few tens of volts (∼30 volts) per L-shell.

Another possible explanation for this shift is that it may be the
result of some sort of low energy cutoff or selection mechanism which
is a function of time, latitude, and/or longitude. Again the most in-
teresting and also most probable dependence would be one of latitude.
This would then mean that as the solar wind particles were transported
to field lines which extend to higher magnetic latitudes there is some
mechanism which excludes the lower energies. Such a process is
difficult to visualize if these field lines are closed but constitute the outer boundary of the trapped radiation. The source of the plasma would then be within the magnetosphere with diffusion or some other transport mechanism acting to draw the particles to higher magnetic latitudes. As discussed above, there exist arguments, though weak, that the original source of this particle flux is the solar wind or plasma sheet. Consequently we would expect this plasma to be transported into the magnetosphere rather than the opposite. If this were the case, the shift indicates that the particle energies are decreased as they move to lower L-shells. This is in direct contradiction to most magnetospheric diffusion or transport theories which instead show from the first invariant (conservation of the magnetic moment) that a plasma should become more energetic as it reaches lower L-shells. Similar arguments may be proposed for an electric field which is perpendicular to closed magnetic field lines.

If, however, it is assumed that the auroral field lines extend into the geomagnetic tail a much more satisfying situation may be obtained. In a model of the magnetosphere such as proposed by Dessler and Juday (1964), Speiser (1965) Dungey (1961), etc. the auroral field lines compose the boundary between the tail region and the magnetosheath, or extend into the plasma sheet. Thus the thermalized solar wind or plasma sheet particles are in direct contact
with the field lines which extend into the auroral zone. As the Twins payloads moved to higher geomagnetic latitudes they sampled the particle flux on field lines which lay more deeply imbedded in the tail region. Thus the interesting possibility is presented that the particles are somehow transferred to these field lines by a perpendicular electric field which energizes this plasma to higher energies as it is moved to tail field lines which map to higher magnetic latitudes. Alternatively, there might exist some type of diffusion process which permits the particles to move into the tail while allowing the higher energy particles to penetrate deeper into the center of the tail.

Still another possible explanation for this shift is an energization of the particles by an electric field parallel to the magnetic field. Such a field is suggested by the observed pitch-angle anisotropy of the flux near 100 ev. As will be shown later (see Figure 33) this flux becomes peaked along the magnetic field as the spectra shift to higher energies. If the continuum flux is indeed the electrons of the plasma sheet or thermalized solar wind a weak electric field, a potential difference of only ~100 volts, would be detectable by a change in the energy and pitch-angle distribution of only the lower energy (~100 ev) particles. This is indeed observed in the continuum spectra. Again, this source of energization, i.e. a parallel electric field, may be a function of time, latitude, and/or longitude.
In summary the Twins experiment has shown that the electron fluxes present in a weak diffuse aurora possess an energy spectrum which may be approximated by a power law between the energies of 100 ev and ~25 kev,

\[ N(E) = N_0 E^{-1.3 \pm 0.3} . \]

This spectrum has a peak intensity at ~100 ev, and a gradual shift of this peak to higher energies with time, latitude, and/or longitude. This continuum spectrum appears to have the characteristics of the electrons in the plasma sheet of the magnetotail. Though it cannot be definitely proven with this one experiment, it is suggested that this particle flux is actually the plasma sheet particles of the magnetotail which have managed to reach auroral altitudes. The data is then most consistent with the magnetospheric models which allow the auroral zone field lines to extend into the tail region i.e., Dessler and Juday (1964), Speiser (1965), etc.

From study of the all-sky camera photographs it was determined that the payloads had passed over an auroral arc at 60 seconds and at 170 seconds after separation. The precipitated electron energy spectra for these periods contain a characteristic peak in their spectrum near 6 kev. This prominent feature is easily recognized in a quick scan of the data. It appears on four
distinct occasions during the flight as shown in Figure 25. The last
two spectra in this figure could not be definitively associated with
bright auroral arcs because the 100 km level below the payloads was
then too near the horizon for adequate photographic resolution at
these times. However, the all-sky camera photographs do show a
general enhancement of activity in this region. Consequently it is
assumed that this peaked spectrum is characteristic of the electron
energy spectrum causing the brighter luminosities associated with
an auroral arc.

The quiet diffuse electron energy spectra is still present
in these spectra. The peak rises out of the original spectra and
then disappears again after the payloads have moved across and
away from the arc.

An important point to note is that the spectrum within the
arc is definitely not mono-energetic. Several experimenters, such
as Evans (1967) and Albert (1967), have recently seen a peaked
spectrum similar to these. Samples of their data are shown in
Figures 1 and 29. The lowest energies seen by them were near
1 kev. Consequently the peak which they saw appeared to be what
they called "nearly mono-energetic". However, the Twins, by ex-
tending the spectrum to lower energies, have shown this to be not
the case. In fact the flux continues to rise monotonically to another
peak near 100 ev. This feature of the electron energy spectrum
remains constant throughout the precipitation event.

The intensity of the continuum flux undergoes no appreciable
change, beyond statistical limits, during the onset and decay of the
peaked spectrum. The small and steady drift of the continuum spec-
trum to higher energies remains during these periods also.

The total integrated energy contained in the peak of the first
spectrum (T=56-75 sec., Figure 25) is near an order of magnitude
more than the total energy contained in the continuum. This con-
tinuum may be approximated by a power law spectrum between the
energies of 50 ev and 20 kev,

$$N(E)dE = N_0 E^{-\gamma} dE.$$ 

Thus the total energy is determined by integrating this equation over
energy. The best fit to this continuum spectrum requires the exponent
to be $\gamma=1$. Therefore:

$$E_t = \int_0^{20} N(E)EdE = N_0 \int_0^{20} dE = 20 N_0 \text{ (kev)}$$

where $N_0$ is the flux at 1 kev. Numerical integration of the energy
contained in the peak yields a value of 258 $N_0$ (kev). Therefore the
peak contains a factor of 12.9 times the energy contained in the con-
tinuum. If the physical geometric factor is assumed to be $1.6 \times 10^{-5}$ cm$^2$
ster, as determined from the Ni$^{63}$ calibrations, $N_0$ will have a value of
$1.9 \times 10^8$. The energy in the peak then becomes 77.4 ergs/cm$^2$ sec ster.
while that of the continuum is 6.0 ergs/cm² sec ster.

An increase in the energy influx by a factor of ~13 should also be reflected in the ground photometer data (Figure 23). Unfortunately, the 3914 Å emissions increased so rapidly at this time that the recording instruments went off scale for a short period. Also, the photometer's field of view which was periodically changed to follow the rocket trajectory, was moved to a new look angle before the peak intensity was obtained. However, it is possible to place a lower limit of a factor of ~5 on the increase in the 3914 Å emissions. Considering the above problems plus the fact that the photometer probably did not have the auroral arc filling its field of view, there appears to be good agreement, better than a factor of two, in the energy influx variations as detected by SPECS and the 3914 Å photometer data.

The physical geometric factor derived earlier can now be checked by comparing the energy input as measured by SPECS with the energy input predicted by the ground-based photometric measurements. The continuum electron energy spectrum remains fairly constant from T = 0 seconds up to and within the first auroral arc. The 3914 Å light intensity indicates ~6.0 kR were produced in this region. Delagarno et al. (1965) have found the relation of 3914 Å intensity to electron energy input to be approximately 1.2 ergs/kR (3914). Consequently the photometric measurements indicate an energy input of
\( \sim 7 \text{ ergs cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1} \). This value compares extraordinarily well with the SPECS data which indicates \( 6 \text{ ergs cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1} \). As a further verification of the geometric factor the energy balance was checked again at \( T = 350 \text{ seconds} \). In this region both the electron spectrum and light intensity were quite stable. The 3914 Å intensity indicated an energy input of \( 3.76 \text{ ergs cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1} \) and SPECS measured \( 2.0 \text{ ergs cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1} \). Again, considering all the possible errors which might come into play, this agreement is surprisingly close. However, this agreement should not be construed to mean an absolute verification of either the SPECS geometric factors or Dalgarno's theoretical results. It simply lends credibility to the SPECS data presented here.

The "typical" auroral electron energy spectrum is depicted in Figure 30. This figure is intended to bracket every valid precipitated electron spectra (\( \sim 230 \) spectra) obtained by SPECS on this flight. Each of these spectra will lie within the shaded region of Figure 30 provided an appropriate normalization of the total flux level is made. Thus this figure represents the range of average, or typical, electron energy spectral shape which is associated with an auroral precipitation event. The indicated fluxes correspond to the maximum fluxes encountered. Thus the total flux level of most of the spectra were
normalized upwards by factors of 1 to as much as 10^2.

The Geiger tube data has been included in this spectrum extending it to ~65 kev. As can be seen the spectrum falls off very rapidly above 25 kev. This fact must be considered when evaluating the Geiger tube data. The Geiger tubes were integral detectors of electrons with energies greater than 60 kev. However, since the spectrum is extremely steep at these higher energies, the main contribution to the count-rate will be due to particles near 60 kev and bremsstrahlung from lower energy electrons. Therefore, neglecting this bremsstrahlung, the Geiger tube may be considered a differential energy detector with a passband given by folding the energy spectrum into the Geiger tube's energy response curve. This has been done for the spectrum in Figure 30 and resulted in an effective energy passband of ~10 kev centered at 65 kev.

However, the bremsstrahlung, which has been neglected, most certainly contributes to the count-rate of the detector. The flux as determined in this manner thus represents only an upper limit on the true differential flux of 65 kev electrons. If the bremsstrahlung contamination is appreciable one would expect good correlation between the Geiger tube data and the lower energy fluxes measured by SPECS. The data do show qualitative correlation up to ~600 seconds after separation. At this time the lower energy flux measured by SPECS and also the
D.E.D. detectors abruptly drops by several orders of magnitude and remains at an extremely low level for the next 200 seconds, at which time the payloads re-entered the atmosphere. However, no change, beyond the counting statistical limits of ~7%, can be detected in the Geiger tube flux at this time. In fact the flux detected by the Geiger remains fairly constant through the remainder of the flight. Thus an upper limit of 7% may be set on the contamination to the Geiger tube count rate due to bremsstrahlung from lower energy electrons. This is based on the assumption that the >60 kev electrons did not increase by precisely the correct factor at precisely the correct time in order to offset the decrease in contamination from the lower energy electrons. Even if this unlikely set of events did occur, the Geiger tube data still sets an upper limit on the higher energy (>60 kev) electrons.

A mathematical description of the spectrum in Figure 30 may be provided by two power laws for the two regions on either side of ~25 kev. Below 25 kev an exponent of (-1.3 ± 0.3) will usually fit the continuum spectrum quite well. Above 25 kev the exponent must be at least (-10 ± 1) to fit the Geiger tube data.

The maximum total energy carried by the particles above 25 kev has been calculated to be no more than 0.1 ergs cm⁻² sec⁻¹ ster⁻¹ at any time in the flight. This energy is negligible compared to the energy carried by the electrons of less than 25 kev energy. Thus it is
permissible to neglect electrons of energies greater than 25 kev when performing energy balance calculations as above. Furthermore this points out the fact that it is the lower energy electrons which predominate the visual auroral phenomena by carrying more than 90% of the energy influx. Consequently when a study of auroral particles per se is attempted one should concentrate on these lower energy particles instead of those greater than 40 kev as has often been done in the past.

Turning now to the question of the source of this energetic electron flux which produces the auroral arcs (Figure 25), we are confronted with one of the most serious problems in auroral physics. There have been many proposed models for this source, most of which involve some configuration of electric fields, or time-varying magnetic fields which when viewed in the proper frame of reference may be considered electric fields also. In addition to these somewhat static fields there have also been proposed several dynamical models such as wave-particle interactions which excite electrons to certain favored energies, thereby producing a "mono-energetic", or at least peaked, electron energy spectrum. The discussion which follows will attempt to select the actual process by comparing their predictions with the Twins data.

The data presented here seem to indicate that there are at
least two processes involved in the source of the precipitated auroral particle flux. As discussed earlier the continuum spectrum is quite similar to the spectrum of the plasma sheet electrons as well as the thermalized solar wind electrons. Thus it has been suggested that the continuum electrons have their source in the plasma sheet, while these in turn may have their source in the thermalized solar wind. On the other hand, the flux contained in the peak which appears in the spectra associated with the auroral arcs does not have a similar "parent source" with which it can be readily identified. The continuum particles are present both within and at higher and lower latitudes on either side of the arcs. Thus it is not unreasonable to assume that the particles in the peak have the same source as the continuum particles, i.e. possibly the plasma sheet and thermalized solar wind. This is indeed suggested by the slight indication of a 10 kev peak in Montgomery's plasma sheet data (Figure 28). However, the source of this peak in the plasma sheet spectra is also unknown. Since there is no readily available reservoir of 10 kev particles, there must be some mechanism which energizes these continuum or plasma sheet electrons to energies near 10 kev.

One possible mechanism is an electro-static field parallel to the magnetic field. Such fields at low altitudes (<1000 km) have been proposed by Mozer and Bruston (1966) and McDiarmid et al. (1967) to
explain anomalous pitch-angle distributions. However, these fields have great difficulty explaining the observed proton precipitation and also would appear to have drastic effects on the ionosphere itself. In addition, the Twins data cannot support the existence of these fields for several reasons. As will be shown later the pitch-angle distribution of the fluxes in the peak is purely isotropic for the downward moving particles. A low altitude electric field parallel to $\mathbf{B}$ would most certainly cause a pitch-angle distribution peaked along the magnetic field at flight altitudes above the appreciable atmosphere. Furthermore, the continuum spectrum is not effected whatsoever during the presence of this peak. An electric field even at high altitudes would eliminate this continuum spectrum or at least change its shape appreciably. This is of course based on the assumption, that the continuum particles passed through the region containing the electric field.

Another possible orientation of the electric field which may energize charged particles is a field perpendicular to the magnetic field. Such an electric field has been proposed by several groups such as Speiser (1965), Dungey (1958), Taylor and Hones (1965), Albert (1967). The locations, directions, and magnitudes of the fields vary greatly between these models. However, they all contain the same basic mechanism of the particles drifting across the
magnetic field lines to regions of higher electrostatic potential and thereby an energization of the particles themselves. The electric fields proposed are of necessity quite high, on the order of kilovolts per L-shell. Therefore the energy of the peak should change by a detectable amount as one crosses L-shells. In the case of the Taylor and Hones model the energy should increase with an increase to higher latitudes. The Twins data, however, show no appreciable change in the peak energy even though the payloads crossed approximately three (≈9 to ≈12) L-shells to the north. In addition these theories do not account for the continuum spectrum which is most certainly present even within the auroral arcs. The above arguments suggest that electrostatic fields are probably not the source of the peaked spectrum producing the auroral arcs.

There are other mechanisms which might be proposed to explain the auroral fluxes detected by the Twins experiment. Among these are wave-particle interactions which can accelerate particles to higher energies. For example Smullin and Getty (1962) have reported a laboratory experiment in which the injection of a mono-energetic beam of electrons into a plasma containing a magnetic field has caused the production of a heated plasma. Stix (1964) has shown that this is probably the result of the interaction of the beam with the plasma producing various modes of plasma waves. A resonance between the
gyrofrequency of the electrons and the wave frequencies can lead to a transfer of energy from the waves back to the particles, accelerating them to higher energies.

It is well known (c.f. Stix, 1964) that an anisotropic pitch-angle distribution of low energy plasma may also lead to plasma instabilities and thereby plasma waves. Therefore, it is possible to conjecture upon the possibility of such a process occurring in the auroral fluxes. The low-energy continuum is certainly anisotropic, as will be shown later, with approximately an order of magnitude more particles moving down the field lines than up. Consequently it seems possible that a plasma instability may occur which produces plasma waves with frequencies resonant with the continuum electrons accelerating them to higher energies. If the various parameters of the plasma (e.g. magnetic field and plasma density) vary in a fortuitous manner along the magnetic field lines, a peaked energy spectrum might even be obtained. One of the main objections to wave-particle interactions as applied to auroral phenomena, has been the difficulty of generating waves which contain enough total energy to drive an aurora. However, since these waves act only as a catalyst for the transfer of energy, they need not contain a large amount of energy themselves.

A model such as this might be supported by the Twins data. While the above discussion is pure conjecture, it does seem to be
a possible mechanism for energization of the auroral particles. Since no other theory or model seems to be adequate to explain this energization and also the other auroral particle flux characteristics, this model should be investigated and developed in detail.

C. AURORAL ELECTRON PITCH-ANGLE DISTRIBUTIONS

The SPECS detectors on Twins I made not only energy spectral measurements but also measured the pitch-angle distribution of these spectra. The SPECS were oriented in the payload so that they detected particles coming from a direction 45° to the payload spin axis. The downward-viewing SPECS of each Twin was mounted along the same direction but antiparallel to the upward-viewing SPECS. The spin axes of the two Twins were parallel and at a 25° angle to the magnetic field after separation. Consequently, the SPECS detectors determined the pitch-angle distributions of the energy spectra between 20° and 70° for the downward moving particles and between 110° and 160° for the upward moving particles.

The angular field of view of SPECS is not circular but measures approximately 4° by 20°. The detectors were oriented such that the 4° angle would lie in the plane containing the spin axis. Therefore, at any point in the spin period, SPECS detected particles with a resolution of ±2° in pitch-angle and ±10° in azimuth. However, the particle flux
may be assumed to be isotropic in azimuth, i.e. the angle about the magnetic field. This is a result of the particle’s gyro-radii being negligible with respect to their mean free path or electric-field effects which may cause a drift of the particles across the magnetic field. Thus any variation in the flux with the spin of the payloads is due to the pitch-angle distribution. The spin rate, telemetry sampling rate and payload orientation all combined to cause the SPECS detectors to sweep through a pitch-angle interval of approximately 4° in one telemetry sample period. Thus the pitch-angle distributions are sampled in approximately 4° contiguous segments.

As mentioned earlier, each frame also contained the 45° magnetometer data. This magnetometer was aligned parallel to the SPECS detectors. Thus the pitch-angle being observed can be calculated for each frame. As can be seen in Figure 31, the magnetic field intensity changes by nearly 50% in the altitude range of the Twins flight. This fact must be considered in the computation of the pitch-angles. This was done by assuming that the payload spin vector did not change its orientation with respect to the magnetic field vector throughout the flight. This assumption is valid due to the observed stability of the payloads and the fact that the trajectory was nearly parallel to the constant 6° dip contour as mapped by geodetic surveys. Thus it may be assumed that the maximum and minimum excursions of the sine wave
produced by the magnetometer output correspond to the maximum and minimum pitch-angles, i.e. 70° and 20°. The running averages of these maximum and minimum values were routinely calculated in the computer analysis and the pitch-angles computed for each frame by scaling the magnetometer sine wave to these values.

The electron energy spectra as a function of pitch-angle were obtained from the data by a computer program which sorted the data according to the magnetometer output. Approximately ten to twenty seconds of data were analyzed to obtain each pitch-angle distribution. Thus each spectrum presented here represents at least 100 sweeps through the pitch-angle distribution. In order to insure against temporal variations obscuring the true pitch-angle distributions, several sampling intervals were tried. However, the final pitch-angle distribution did not change appreciably over sampling intervals of three seconds to twenty seconds. Therefore, to obtain good statistics, a lower limit of ten seconds was set for the sampling interval.

Typical results of this analysis are shown in Figures 32 and 33. The precipitated electrons, pitch-angles 20° to 70°, are seen to be almost purely isotropic independent of the energy (Figure 32). This isotropy is preserved both in the presence and the absence of the peak in the spectrum early in the flight. With the appearance of the peak in the lowest energy channels and as this peak slowly shifts to higher
energies, the fluxes at these lowest energies become anisotropic. The flux becomes peaked along the magnetic field at energies near 100 ev as can be seen in Figure 33. This anisotropy cannot be explained as instrumental or as an altitude effect, but is characteristic of the particles themselves. As discussed earlier, one implication of this result is the existence of weak parallel electric fields which not only would result in this pitch-angle distribution but may also cause the slight energization of the continuum spectra.

Above a few hundred ev the downward moving electrons remain isotropic at all times during the flight. From Figure 31 it is noted that the loss cone has decreased to nearly 55° at apogee. Therefore, near apogee the SPECS were observing "trapped" particles at pitch-angles of 55° to 70°. It is interesting to note (Figure 33) that the isotropy persists even into this trapping region. Thus the energy spectrum and flux levels of the downward moving particles are identical in both the loss cone and the trapping cone. In other words there appears to be no distinction in the particles themselves between these two regions. This isotropy persists even when the flux intensities change by an order of magnitude.

One implication of this result is that the trapping region does not really exist on these field lines. If the particles in the trapping region were stably trapped, the temporal behavior over short time
intervals would not necessarily be identical to that of the flux in the loss cone which has been freshly injected or energized. For example if the source is suddenly turned off, the particle flux in the trapping region would be expected to remain at a constant level with perhaps a slow decrease in intensity with a time constant of more than one bounce period (≈ 1 sec.). This is definitely not the case in the Twins data where the flux intensities of the trapping region follow identically all variations of the flux in the loss cone. Some of these variations are as much as a factor of ten in time intervals of less than 500 msec. Thus there appears to be a very effective loss mechanism associated with these particles which would otherwise be durably trapped. This loss mechanism may take the form of an extremely efficient source of scattering located somewhere along the field lines. However, such a scattering mechanism would have to be capable of producing complete isotropy in the particle flux within only one bounce period (≈ 1 sec. @ 10 keV).

Another possibility might be the loss of the particle fluxes in the opposite hemisphere. However, it has been calculated using the computer program of McIlwain (1961) that the mirroring altitude in the southern hemisphere conjugate to Ft. Churchill is actually higher by approximately 100 km. Consequently this does not seem to be an efficient loss mechanism for the higher energy (≈ 10 keV) particles.

Still another possibility, would be a loss of the particles simply
by their magnetic drift in longitude. There is, however, no reason to believe that the electron flux to the west of the payloads vary in precisely the correct manner such that after they have drifted around to the east they are exactly in phase with the fluxes at the payload.

On the other hand, assume the magnetic field lines at the payloads extend into the tail, in such a manner that the particles may not bounce between hemispheres and become trapped. The Twins data would easily support such a model. In this case all of the particle flux would be freshly injected or energized, and there would be no distinction in the particles themselves between a trapping and loss cone. This also would agree with the magnetospheric models of Dessler and Juday (1965) and also Speiser (1965). The Twins data alone cannot prove that the field lines are "open" and extend into the tail, or "closed" in the classical dipole sense. In summary they have shown that if the field lines are "closed", i.e. within the magnetosphere itself, then there must exist an unexpected and extremely efficient loss mechanism which prevents durable trapping on these field lines. Alternatively, the data are easily explained by the hypothesis that the auroral zone field lines extend into the tail, and hence the particles are unable to execute complete traversals of the field lines between hemispheres.

In Figures 32 and 33 the lower spectrum is that of the
backscattered or upward moving electrons. Here we note that the pitch-angle distribution is energy dependent. The flux is purely isotropic up to approximately 1 kev. It then becomes anisotropic with the electron flux nearer 90° pitch-angles being more intense. This anisotropy is in qualitative agreement with simple Coulomb scattering theories. An electron with an initial pitch-angle near 90° will not penetrate as much atmosphere as one near 0° pitch-angles. Consequently it has less probability of being absorbed or scattered in the atmosphere and the return pitch-angle distribution would be more intense nearer 90° than 180°. However, at the lower energies the returning spectrum consists not only of particles with the corresponding initial energy and pitch-angle but also of particles which had higher initial energies and had undergone a few collisions with atmospheric particles. These scattered particles have a nearly isotropic distribution and obscure any pitch-angle distribution which may have been there initially. At present there exists no quantitative theory for the atmospheric interactions of electrons in this energy range (<20 kev). This is due to a lack of information on the cross-sections for the interactions involved at these energies. The data presented here could possibly be used to measure these cross-sections or at least provide a test of any theory which might be proposed.
IV. SUMMARY OF RESULTS AND CONCLUSIONS

The Twins I experiment was successfully launched into an IBC I-II aurora over Fort Churchill, Manitoba on 18 March 1967. The aurora was characterized by a diffuse glow across the sky of \( \sim 5 \text{ kR} \) 3914 \( \AA \) and contained several arcs with more than 25 kR 3914 \( \AA \) over which the Twins' payloads passed. The electron differential energy spectrum observed outside of these arcs was characterized, at all times during the precipitation event, by a power law of the form,

\[
N(E)dE = N_0 E^{-(1.3 \pm 0.3)}dE,
\]

between the energies of \( \sim 100 \text{ ev} \) and \( \sim 25 \text{ kev} \). This characteristic spectrum has been referred to as the continuum, and is present even in the electron fluxes which produce the brighter auroral arcs. The continuum reaches its peak flux near \( \sim 100 \text{ ev} \), with a gradual shift of this peak to higher energies with time, latitude, and/or longitude. The proton fluxes observed during the flight were below the limit of detectability of the SPECS detector. Thus only an upper limit of \( \sim 10\% \) of the electron flux at the same energies may be placed on the auroral proton fluxes.

The precipitated electron energy spectrum which produces the brighter auroral arcs is characterized by a peak in the vicinity
of ~6 kev. Contrary to other observations (c.f. Evans, 1967, and Albert, 1967), this spectrum has been shown to be definitely not "mono-energetic". The total energy carried by the particles in this peak is near an order of magnitude more than the total energy in the continuum. Comparison of the energy deposition in the aurora as measured by SPECS and the ground-based photometers is in reasonably close agreement with Dalgarno's theoretical predictions (Dalgarno, 1965).

Though the average or typical electron spectrum is relatively "hard" up to 25 kev, the slope of the spectrum is extremely steep above this energy. The power law description of the spectrum changes from an exponent of (-1.3 ± 0.3) below 25 kev to (-10 ± 1.0) above 25 kev. Thus it is demonstrated that the majority of the energy influx is carried by electrons of less than ~25 kev and that these lower energy particles are the ones which should be investigated in detail when studying the visual auroral phenomenon.

The pitch-angle distribution of the precipitated electrons was shown to be purely isotropic at all times during the flight for energies above ~1 kev. Below this energy the fluxes became peaked parallel to the magnetic field as the low energy (~100 ev) peak shifts to higher energies. The backscattered electrons are isotropic below 1 kev but become peaked perpendicular to the magnetic field above this energy.
This distribution is in qualitative agreement with simple atmospheric scattering theories. The data should provide excellent experimental tests for any detailed theoretical analysis which as yet remains to be performed at these lower energies.

The "transit-time" and "coherence size" portions of this experiment have not been treated here. These measurements were of an exploratory nature and no conclusive results were obtained from this flight. However, as a result of the data taken by Twins I the scientific detector complement of Twins II has been greatly refined and improved with respect to these goals. Thus definitive "transit-time" and "coherence size" studies are awaiting the launch and analysis of the Twins II flight.

The auroral phenomenon is extremely variable and complex by nature. Comparison of the results of a single experiment flown into one aurora cannot, of course, prove conclusively the validity of any particular theoretical model of the auroral phenomenon. Instead many sophisticated and powerful experiments are required from which a statistical or typical behavior may be determined. An attempt can then be made to compare these typical characteristics with detailed theory.

The results from the Twins experiment have contributed much new and very complete information on the electron fluxes which
produce the visual aurora. An attempt has been made to compare the characteristics of these fluxes with those predicted by various auroral theories or models. The results indicate that the auroral zone electron fluxes probably originate in the plasma sheet of the geomagnetic tail. The data are most consistent with magnetospheric models which allow the auroral zone field lines to extend into the tail region. Varying degrees of inconsistencies have been found when the data are compared to theories utilizing electro-static fields, either perpendicular or parallel to the magnetic field, as a source of energization of these particles.
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FIGURE CAPTIONS

Figure 1: Electron energy spectra observed on a rocket flight launched at 2153 U.T. on September 16, 1966 (from Albert, 1967). The downflux spectra correspond to pitch-angles of 80° and the upflux spectra to 100°.

Figure 2: Typical pitch-angle distributions of >40 kev electrons at 1000 km altitude and high latitudes (from O'Brien, 1962).

Figure 3: Twins I separation sequence. Nose cone separation occurs 120 sec. after launch at an altitude of 200 km.

Figure 4: Dispersion contours of the relative separation velocity vector projected into the plane perpendicular to the magnetic field vector. The angle Θc is the final coning angle of the Twins before separation. The axis labeled V∥ lies in the plane of the Twins' trajectory.

Figure 5: Photograph of the Twins payload including Twin IA, Twin IB, and the extension tube.

Figure 6: Photograph of Twin IA showing in detail the arrangement of the instrumentation.

Figure 7: Assembly drawing of the Twins I payload.

Figure 8: Block diagram of the P.C.M. data encoding system.
Figure 9: Twins I trajectory as determined by the Churchill Research Range radar tracking station. Altitude is measured from mean sea level and range from the launch site. The time scale is defined as $T=0$ sec. at Twin-Twin separation.

Figure 10: Orientations of the detector fields of view in the Twins I payloads. The D, E, D, detectors and Geiger tube are aligned parallel to the payload spin axis. The two SPECS detectors and one magnetometer are parallel and at a $45^\circ$ angle to this axis.

Figure 11: Sketch showing the operation of SPECS detector (from O'Brien et al., 1967). With a positive voltage on the lower deflection plate, electrons are deflected down to the five channeltrons while protons are deflected up into the funnel channeltron.

Figure 12: Illustration of typical energy passbands of the SPECS detector. The deflection plate voltage is indicated by $V$ and the second subscript on each passband. The first subscript indicates the particular channeltron. Channel 6 (dashed line) detects particles with the opposite charge of those entering the five other channeltrons.

Figure 13: Typical calibration curves for one channel of SPECS. Each curve corresponds to a mono-energetic electron beam at the labeled energy as a function of $\Theta$ (Figure 15).
Figure 14: Energy passband calibration curves for all four SPECS at a deflection voltage of 350 V. To obtain the passbands at the 35 V and 3500 V deflection voltages, the energy scale is shifted by a factor of $10^{-1}$ or $10^1$ respectively.

Figure 15: Schematic illustration of the geometry of the SPECS front end.

Figure 16: Theoretical one-atom electron energy spectrum of Ni$^{63}$. The actual spectrum from a thinly plated source is shifted to lower energies and becomes much softer. (from Hogan, 1964).

Figure 17: True versus apparent count rate calibration curves of the two Geiger tube detectors flown on Twins I. The incident flux is the rate at which the particles enter the tube, while the detector count-rate is the count-rate (apparent) produced by the tube. The geometric factor of $3 \text{ cm}^{-2} \text{ ster}^{-1}$ has not been used in this figure.

Figure 18: Sectional drawing of the D.E.D. detector deflection system. The cylindrical deflection plate in the center is at a positive voltage so that electrons are deflected towards the channeltron with a certain energy focused on the channeltron aperture.

Figure 19: Twin-Twin orientations after separation. The payload spin axes are parallel and at a 25° angle to the magnetic field vector. The
relative separation and relative horizontal separation velocities are shown.

**Figure 20:** Block diagram of the Twin IA velocity transducer electronics and its subcommutation with the SPECS detector.

**Figure 21:** Twins I magnetometer calibration curve. The digital value of the P.C.M. telemetry output is shown as a function of the magnetic field component measured by the 45° magnetometers.

**Figure 22:** Orientations of the 45° magnetometer at two points in the spin period. The payload spin vector ($\vec{\omega}$) magnetic field vector ($\vec{B}$) and the maximum ($\theta_0$) and minimum ($\theta_1$) angles of the 45° magnetometer with respect to the magnetic field vector shown.

**Figure 23:** The 3914 Å intensity measured by the ground photometers. The intensity has been corrected for both the Van Rihjn and atmospheric absorption. The field of view of the photometer was changed periodically to follow the trajectory as projected along the magnetic field to 100 km altitude.

**Figure 24:** Typical precipitated auroral electron differential energy spectra which are associated with quiet diffuse aurora. Times are measured from Twin-Twin separation. The fluxes may be converted to particles cm$^{-2}$ sec$^{-1}$ ster$^{-1}$ kev$^{-1}$ by multiplying by a factor of
$10^5$. Each spectral point represents a half second average and thus approximately 5 sweeps through the pitch-angle distribution from $\alpha=20^\circ$ to $70^\circ$. The error bars on each point due to statistics alone are less than 10%. The scatter of the points are due to fluctuations in the auroral particle flux itself.

**Figure 25:** Same as Figure 24 except typical of the auroral flux causing the auroral arcs.

**Figure 26:** Sketch of the differential electron energy spectra to be found in various regions of space (from O'Brien, 1966). The envelopes do not necessarily represent the shape of the spectra but are intended to bracket nearly all measurements made to date.

**Figure 27:** Typical electron and proton differential energy spectra obtained by OGO 3 in the magnetosheath (from Frank, 1967). The position of the satellite (the gap in the orbit) is also shown.

**Figure 28:** Representative electron differential energy spectra obtained by the Vela 2 satellite in the plasma sheet (from Montgomery, 1968). Curve 8 represents the sum of two Maxwell-Boltzmann flux curves chosen to have about the same peak height and position as the other curves.

**Figure 29:** Representative examples of the electron energy spectra
above an auroral arc (from Evans, 1967).

**Figure 30:** Sketch of the electron differential energy spectrum encountered by the Twins I experiment. The energy range has been extended to include Geiger tube data. Every spectra obtained on this flight during the precipitation event can be forced to fall within the contours shown in this figure with only a normalization of the total flux levels. The flux levels shown correspond to the maximums encountered during the flight.

**Figure 31:** Magnetic field intensity and the loss cone for 500 ev and 10 kev electrons as a function of altitude over Ft. Churchill, Canada. The loss cones are defined as $90^\circ$ at 200 km and 100 km for 500 ev and 10 kev electrons respectively.

**Figure 32:** Differential electron energy spectra at various pitch-angles obtained at an altitude of ~430 km and within an auroral arc. The spectra at six different pitch-angles ($20^\circ$, $45^\circ$, $70^\circ$, $110^\circ$, $135^\circ$, $160^\circ$) are superimposed in this figure. The precipitated electrons are purely isotropic with each data point lying within the points shown. The backscattered electrons are anisotropic with the spectra at the different pitch-angles labeled by $\alpha$. Ten second averages were used corresponding to approximately 100 samples of each pitch-angle, leading to statistical errors of $<10\%$ in the worst case.
Figure 33: Same as Figure 32 except the data was obtained near the apogee of 794 km. The loss cone for 10 kev electrons is $\sim 60^\circ$ at this altitude.
MIRRORING ALTITUDE (KM)

INJUN I ELECTRONS E ≥ 40KEV

0435 Z
JUNE 30, 1961

0 500 1000 500 0

0 10^3 10^2 10^1

NORMALIZED COUNTING RATE

DETECTOR FIELD OF VIEW

PITCH ANGLE (α)°

1945 Z
JUNE 30, 1961

150 130 110 90 70 50 30

150 130 110 90 70 50 30

10^3 10^2 10^1

MIRRORING ALTITUDE (KM)

FIGURE 2
TWINS I SEPARATION SEQUENCE

TWIN-TWIN SEPARATION

$T = 25 \text{ sec.}$

FOURTH STAGE SEPARATION

$T = 3 \text{ sec.}$

NOSE CONE SEPARATION

$T = 0 \text{ sec.}$

FIGURE 3
HORIZONTAL COMPONENTS OF THE RELATIVE SEPARATION VELOCITY VECTOR

\[ V_{\parallel} (m/sec) \]

\[ V_{\perp} (m/sec) \]

\[ \theta_c = 12^\circ \]

\[ 8^\circ \]

\[ 4^\circ \]

\[ 0.5 \]

\[ -0.5 \]

\[ 1.0 \]

\[ -1.0 \]

\[ 0.5 \]

\[ -0.5 \]

FIGURE 4
PCM ENCODER

FIGURE 8
TWINS I
TRAJECTORY

ALTITUDE (KM)

APOGEE
794 km

ALTITUDE

TWIN-TWIN
SEPARATION
273 KM

RANGE (KM)

T = 0 SEC. = 0549:18 U. T.
18 MARCH, 1967

TIME FROM SEPARATION T (SEC)

FIGURE 9
TWINS I
DETECTOR ORIENTATION

Lo DED  Hi DED  Geiger  SPECS

Magnetometers

Lo DED  SPECS

FIGURE 10  201353
Sixth & Funnel Channeltron

Five 270° Channeltrons

Electrons

Protons

Particles In

Figure 11
ENERGY PASSBANDS OF "SPECS"

V ~ 3.5 keV

V ~ 350 volts

V ~ 35 volts

PARTICLE ENERGY (keV)
SPEC ENERGY PASS-BANDS
(DEFLECTION PLATE VOLTAGE, 350V)

TWIN IA (UP)

CHANNEL 6

TWIN IA (DOWN)

CHANNEL 6

TWIN IB (UP)

CHANNEL 6

TWIN IB (DOWN)

CHANNEL 6

RELATIVE RESPONSE (cts sec⁻¹ ster⁻¹)

ELECTRON ENERGY (KEV)

FIGURE 14
Figure 15
THEORETICAL Ni$^{63}$ ELECTRON ENERGY SPECTRUM

![Graph showing relative intensity versus electron energy in KEV.](image)

**Figure 16**
TWINS I GEIGER TUBES
TRUE vs. APPARENT COUNT RATES

$X = \text{TWIN IA}$
$O = \text{TWIN IB}$

**Figure 17**
D.E.D. DETECTOR

CHANNELTRON

CROSS SECTION

FIGURE 10
TWIN-TWIN ORIENTATION

\[ \omega = 8.8 \text{ rev.-sec}^{-1} \]
\[ V_{rs} = 2.64 \text{ m-sec}^{-1} \]
\[ V_{hs} = 1.11 \text{ m-sec}^{-1} \]

**Figure 19**
MAGNETOMETER ORIENTATIONS

\[
\begin{align*}
\theta_1 & \quad \theta \\
45^\circ & \quad 45^\circ \\
\end{align*}
\]

FIGURE 22
TWINS IB
PRECIPITATED AURORAL ELECTRONS

COUNTS (SEC$^{-1}$ KEV$^{-1}$)

$T=101-115$ sec.
ALT. = 550 km.

$T=211-225$ sec.
ALT. = 700 km.

$T=347-361$ sec.
ALT. = 794 km.

$T=563-577$ sec.
ALT. = 630 km.

ELECTRON ENERGY (KEV)

FIGURE 24
TWINS IB
PRECIPITATED AURORAL ELECTRONS

COUNTS (KEV"1 SEC"1)

T=56-75 sec.
ALT.=430 km.

T=164-179 sec.
ALT.=660 km.

T=464-483 sec.
ALT.=750 km.

T=531-543 sec.
ALT.=675 km.

ENERGY (KEV)

FIGURE 25
ENERGY SPECTRA of ELECTRON FLUXES

![Energy Spectra Diagram](image)

**Figure 20**
FIGURE 27
TYPICAL AURORAL ELECTRON ENERGY SPECTRA

FIGURE 30
LOSS CONES AND MAGNETIC FIELD
ABOVE FT. CHURCHILL

MAGNETIC FIELD (gauss)

ALTITUDE (km)

PITCH ANGLE (deg)

FIGURE 31
TWINS IB
ELECTRON ENERGY SPECTRA
VS.
PITCH ANGLE

COUNTS (KEV⁻¹ SEC⁻¹)

PRECIPITATED ELECTRONS
\( \alpha = 20° - 70° \)

BACKSCATTERED ELECTRONS
\( \alpha = 110° - 160° \)

T=59-68 sec.
ALT=430 km.

FIGURE 32
TWINS IB
ELECTRON ENERGY SPECTRA
VERSUS
PITCH ANGLE

\[ \text{COUNTS (KEV}^{-1} \text{ SEC}^{-1}) \]

\[ a = 20^\circ - 70^\circ \]

\[ \text{PRECIPITATED ELECTRONS} \]

\[ a = 110^\circ - 160^\circ \]

\[ \text{BACKSCATTERED ELECTRONS} \]

\[ T = 323 - 333 \text{ sec.} \]

\[ \text{ALT} = 790 \text{ km.} \]

\[ \text{ELECTRON ENERGY (KEV)} \]

\[ a = 110^\circ \]

\[ a = 135^\circ \]

\[ a = 160^\circ \]

FIGURE 33
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