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A study of ion acceleration at rocket altitudes and development and calibration of pitch angle imaging charged particle detectors

Gregory Paul Garbe

University of New Hampshire, Durham

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Abstract
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Keywords
Physics, Fluid and Plasma
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A study of ion acceleration at rocket altitudes and development and calibration of pitch angle imaging charged particle detectors

Garbe, Gregory Paul, Ph.D.

University of New Hampshire, 1990
A STUDY OF ION ACCELERATION AT ROCKET ALTITUDES
AND DEVELOPMENT AND CALIBRATION OF
PITCH ANGLE IMAGING CHARGED PARTICLE DETECTORS

BY

GREGORY PAUL GARBE

B.S., University of Washington, 1986

DISSERTATION

Submitted to the University of New Hampshire
in Partial Fulfillment of
the Requirements for the Degree of

Doctor of Philosophy

in

Physics

December, 1990
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November 27, 1990
Date
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Abstract

A STUDY OF ION ACCELERATION AT ROCKET ALTITUDES
AND DEVELOPMENT AND CALIBRATION OF
PITCH ANGLE IMAGING CHARGED PARTICLE DETECTORS

by

Gregory Paul Garbe
University of New Hampshire, December 1990

Data obtained from the January 1988 flight of the Topaz 2 sounding rocket will be presented. It has been found that four types of ion populations were observed during this flight. During the early portions of the upleg and late portions of the downleg numerical fits of the plasma will be compared with in-situ data to show the Maxwellian behavior and derived plasma parameters. Throughout the middle portion of the flight superthermal tails (ion conics) were observed and are modeled using a bi-Maxwellian distribution function from which $T_{\text{perp}}$ and $T_{\text{par}}$ can be derived. Two other ion populations were observed in the most intense auroral arcs. Transverse accelerated ions (TAI) were observed continuously in these arcs. The individual TAI events were found to have spatial/temporal scales on the order of the analyzer resolution (~1 sec). The characteristic perpendicular energy of the TAI reached as high as 7 eV compared to 1 eV during non-TAI times. High-energy tails have also been observed during TAI events and have perpendicular temperatures in the hundreds of eV. The second ion population found in the arcs of high energy electron precipitation is a cold downflowing population. The typical streaming velocity for this population is 2 km/s. A correlation between the high energy auroral electron precipitation, observed electrostatic oxygen cyclotron waves, cold downflowing ions and the TAI will be presented.

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Introduction

The mission of the solar-terrestrial science community is to be able to describe the processes of the sun-earth environment. The solar coronal atmosphere is continuously radially expanding into space forming what is called the solar wind. The solar wind is comprised of a high temperature fully ionized plasma. As this plasma streams radially away from the sun, it encounters the earth’s dipole magnetic field which causes it to be deflected. This deflection forms what is called the magnetosphere, a region were the earth’s magnetic field is dominate. Because the ions in the magnetosphere carry the majority of the energy, the sources of these ions are of great interest. It was widely thought that magnetospheric ions simply came from the solar wind, however recent observations by satellites have shown that the ionosphere, a region of partially ionized plasma below the magnetosphere, is in fact a major source of magnetospheric ions. The transport of ions from the ionosphere to the magnetosphere can be easily understood by examining the parallel equations of motion in the earth’s magnetic field.

The cyclotron average equation of motion for non-relativistic charge particles traveling parallel to the magnetic field is (Roederer, 1970):

\[ F_{||} = \frac{m}{d} \frac{d\epsilon_{||}}{ds} = q\epsilon_{||} + \frac{GM_E}{r^2} - \frac{M_r\partial B}{B\partial s} + \frac{m}{B} \nabla_{\perp} \cdot \nabla_{\perp} B, \]

Eqn I-1

where \( G \) is the gravitation constant, \( M_E \) is the mass of the earth, \( M_r \) is the magnetic moment, and \( V_D \) is the drift velocity of the particle. The last term in equation I-1 is a second order correction due to the guiding center not following a given field line exactly. In addition because the perpendicular gradient in the magnetic field is small, this term can be ignored. In the high latitude auroral region the magnetic field lines can be considered radial. Thus the parallel energy of a particle can be written as:

\[ P_{||}(s) \approx P_{||}(r) = \int F_{||}(r) dr = q\Phi(r) + \frac{GM_E}{r} - M_r B(r), \]

Eqn I-2
where \( \Phi(r) \) is approximately the electrostatic potential along the magnetic field line. Under the assumption of equipotential field lines (\( \Phi(r) = 0 \)) the condition for gravitational escape can be found when it is recalled that the magnetic moment is simply:

\[
M_n = \frac{m v_\perp(r)^2}{2 B(r^2)}.
\]

and therefore a particle needs only to have

\[
v_\perp(r) \geq \sqrt{2 G \frac{M_n}{r}}.
\]

Thus it has been theorized that the outflow of ions from the ionosphere to the magnetosphere is due to processes in which the ions receive additional transverse energy while traversing up a magnetic field line.

To understand these processes it is first necessary to understand different types of ion populations. Figure I-1 shows the phase space density plots plotted versus velocities perpendicular and parallel to the magnetic field for four different types of ion populations. Figure I-1a shows a stationary Maxwellian distribution which is how one expects to be able to describe a cold ambient plasma. The Maxwellian distribution forms concentric contours about the origin which decrease exponentially with increasing velocity. A cold down flowing ion population is shown in figure I-1b. The down flowing ions are simply a Maxwellian population which has some net motion down the magnetic field line. The third population shown in figure I-1c is transversely accelerated ions. This population has Maxwellian features along the parallel velocity axis and contours which are greatly distorted along the perpendicular axis. This distortion along the perpendicular axis indicates that these particles have received a significant amount of perpendicular velocity as compared to a Maxwellian distribution. The final population shown in figure I-1d is an ion conic. An ion conic is transversely accelerated ions which have convected adiabatically up the magnetic field line via the mirror force given in equation I-1. As the particle gains parallel energy it loses perpendicular energy through the conservation of the particle's total energy. This causes the lobes seen in figure I-1c to fold up as shown in figure I-1d. If this were to
Ion Populations

a) Maxwellian

b) Down Flowing Ions

c) Transversely Accelerated Ions

d) Ion Conic

Figure I-1
be represented in three dimension, the surface of the lobes would form a cone and therefore the naming of the population as ion conics. The observation of either transversely accelerated ions or ion conics in the ionosphere would allow for the identification of that region as a magnetospheric plasma source. It is the goal of this dissertation to discover those time during NASA flight 35.017 at which such populations were present and to associate those mechanism which are the most probable source of the transverse energization.
SECTION 1: NASA FLIGHT 35.017

Review of Ion Heating Physics

Introduction

With the advent of satellites which make in situ measurements of the magnetosphere, it has become apparent that there is an abundant outflow of heavy terrestrial ions from the ionosphere. This process cannot be explained by a single-step parallel acceleration mechanism. However, an increase of their perpendicular energy will allow them to escape via their adiabatic motion. This increase of perpendicular energy has been readily observed in particles detected above acceleration regions. Due to their adiabatic motion, these ions have a cone shaped distribution in velocity space and have thus been referred to as ion conics. While several studies have been performed at these higher altitudes, a minimal number of studies have been performed at the lower altitudes where the transversely heated ions are produced. This lack of observational evidence has led to the development of four different theoretical categories of transverse heating: electromagnetic ion cyclotron resonance [Crew et al. 1990, Chang et al. 1986], lower hybrid resonance [Chang and Coppi 1981, Retterer et al. 1986], electrostatic ion cyclotron turbulence [Ashour-Abdalla et al. 1988, Okuda and Ashour-Abdalla 1983] and narrow potential jumps [Borovsky 1984, Greenspan 1984].

Observations of transversely accelerated ions were first reported by Sharp et al. [1977]. Since this time numerous reports and statistical studies have been made of spacecraft observations of transversely accelerated ions [Klumpar 1985, Yau et al. 1983, Gorney et al. 1981, Ghielmetti et al. 1978]. However most of these reports were from data taken at altitudes above 2500 km. While there exist a limited number of data sets from below 2500 km, there have been no major statistical study done on this region. Past studies have also focused mainly on a single event, satellite pass or phenomena [Peterson et al. 1988, Collin et al. 1986, Klumpar et al. 1984] due to the wide ranging categories of processes involved in transverse heating or the discovery of a unique event. Furthermore, recent searches for
broadband plasma wave signatures coexisting with transverse ion heating have proven extremely difficult [Peterson et al. 1986, Kintner and Gorney 1984].

Reported Observations

Statistical Satellite Surveys. Among the different satellites which have observed ion conics at high altitudes, three data sets have been studied and their statistical results reported. Gorney et al. [1981] tabulated measurements of upflowing ions detected by the electrostatic analysers aboard the S3-3 satellite. Gorney et al. interpreted the data such that periods when the ion flux was maximum along the magnetic field were recorded as ion beams while those times when a relative minimum in the field direction was present were taken to be ion conics. Each event was binned according to the previous definition as well as according to the local time, latitude, altitude, and one of three energy categories (E< 400 eV, 400 eV <E< 2.0 eV, E > 2.0 eV). The frequency of occurrence was defined as:

\[
f_{B, C}(A, B, C) = \frac{\sum_{i,j,k} n_{B, C}(i,j,k)}{\sum_{i,j,k} N_{B, C}(i,j,k)},
\]

Eqn 1-1

where \(\sum_{i,j,k}\) is the sum over local time (\(A\)), latitude (\(B\)), and altitude (\(C\)); \(n_{B, C}(i,j,k)\) is the number of events (\(B, C\): beam or conic) in the bin labeled (\(i,j,k\)), and \(N(i,j,k)\) is the number of samples in a given bin. Gorney et al. used this probability distribution to display the ion beams and conics for the four categories (local time, latitude, energy range, and altitude) during magnetically quiet (\(K_p \leq 3\)) and disturbed (\(K_p > 3\)) times. During quiet times they found ion conics to have a broad maximum from 6:00 to 18:00 local time and uniform observations above 2000 km. During disturbed times conics were found to be uniform in local time and systematically increase in occurrence rate up to 4000 km. During both times conics were associated with the auroral latitudes and had energies primarily below 400 eV. Gorney et al. also pointed out that quiet time conics tended to map down to a source region below 3000 km and when perpendicular conics (transversely accelerated ions) were detected, they were primarily between 1500-2500 km altitude. The authors also
theorized that the increased observation of conics in altitude range during the magnetically disturbed times implied an extended source region for those conics.

A second large statistical study was performed by Peterson et al. [1988] of the DE-1 data. From the outset of this report Peterson et al. state that no 90° conic distributions (transversely accelerated ions) were found in this data. Instead the authors attempted to identify events in which there was a local transfer of energy from plasma waves to ions in the mid-altitude region. The two independent criteria used for this identification was the presence of both intense low frequency (< 1 kHz) plasma wave emissions and a maximum in the energetic ion plasma pressure transverse to the local magnetic field. From this criteria numerous events were identified. Because there was no systematic way in which to present the data, the authors elected to show high time resolution data from three portions of a single satellite crossing of the mid-altitude auroral zone. During these times the upflowing ions are seen to be of low energy (~100 eV) and plasma wave emissions were reported to be at or near multiples of the local hydrogen gyrofrequency. However while these observation are consistent with the transfer of energy from the plasma waves to the ions, it is clearly stated by the authors that no single unambiguous event was found. The authors postulate that three probable reasons for this are: (1) the regions of transverse acceleration are small and therefore had not been sampled by the satellite; (2) the altitude range in which transverse acceleration occurs is limited; and (3) the energy at which the transverse acceleration occurs is below the threshold of the instrument in use.

A second study of the S3-3 data addressed another question of particular interest: is there a mass dependent transverse heating mechanism. Collin et al. [1986] has shown that the energies of the ion beams in this data tended to be higher for O+ then H+ ($E_{O}/E_{H} \approx 1.7$) when compared to the inferred potential drop below the satellite. The authors have tried to show that this difference could by caused by a mass dependent transverse acceleration mechanism acting at lower altitudes. Collin et al. mapped a multi-component ion conic observed by the ion mass spectrometer at 3780 km up through a 5 kV potential drop via an adiabatic process. The resulting distribution was beam-like in appearance and the components mean energy had a ratio of $E_{He}/E_{H} \approx 1.2$ (not enough O+ was detected at this time to be included). The authors state that this result is comparable to the previous found ratio ($E_{O}/E_{H} \approx 1.7$). Therefore the authors argue that acceleration regions below potential drops do indeed have mass dependent transverse acceleration while regions not under
potential drop have an absence of mass dependent acceleration.

**Topside Ionospheric Events.** The trajectory of flight 35.017 took the payload through the topside of the auroral ionosphere. Thus it is important to be able to compare this data to other data from this region. Three reports have been made on transverse acceleration in this region. The S3-3 data was searched for simultaneous observations of transverse acceleration and broadband plasma wave emissions [Kintner and Gorney 1984]. The authors were able to find only one such example. The conics observed during this time extended to energies as high as 1.4 keV and coexisted with intense ~1 keV electron precipitation. The ion flux was also found to obey a power law with an exponential of $P = -2$. The mirror points of all of the conics ranged from 2000 km up to the satellite location of ~2600 km. The plasma waves identified during this time were at and above the lower hybrid resonance frequency. There was a suggestive spatial/temporal correlation between these low-frequency waves and the transverse acceleration but the authors hasten to point out that it was not a conclusive correlation. Kintner and Gorney also determined the "inferred cold electron current density" from the difference of the field-aligned current measured by the electron spectrometer and the onboard magnetometer. The current was found to be 0.5 μamps/m² and implies that electron drift velocity was 0.2% of the thermal electron velocity. While this current was found to correlate well with the transverse acceleration, the calculated drift velocity is stable to electrostatic ion cyclotron waves.

The polar orbiting low altitude (~1400 km) ISIS-2 satellite data was examined by Klumpar [1985]. Klumpar first states that there has been no evidence for parallel acceleration of terrestrial ions in the large data set accumulated by ISIS-2 in the auroral zone therefore showing the outflow of terrestrial ions into the magnetosphere must be due to transverse acceleration processes. The author further points out that the ISIS data shows that it may be sufficient but is not a necessary condition that precipitating auroral electrons be present in order for ions to be transversely accelerated. Instead Klumpar states that upward streaming electrons have been associated with transversely accelerated ions and that the necessary condition for the production of transversely accelerated ions is in fact the existence of a field-aligned current in a reduced plasma density such that instabilities will arise. The association of plasma wave emissions with the transversely accelerated ions
with the ISIS data is made by a high correlation between simultaneously observed VLF saucers and transversely accelerated ions as pointed out by Klumpar. A typical event from the ISIS data is presented. The event was seen for a duration of 2.3 seconds and then abruptly ceased. Under the assumption that the loss of the event was due to the spinning of the satellite out of the event's pitch angle range, Klumpar shows that the lower limit to the source region altitude can be determined as 800 km. VLF saucers were seen coincidentally with the event, while directly afterwards a three order of magnitude jump in the electron flux was seen as the electron detector was pointed towards the loss cone. Thus Klumpar has shown that ISIS data does indeed show a correlation between transversely accelerated ions, VLF saucers and field-aligned currents.

The only report in the literature from previous sounding rocket observations of transversely accelerated ions is by Yau et al. [1983]. The authors described observations made by two separate flights through the topside auroral ionosphere. Rocket IVB-33 was launched from Chuchill, Canada and reached an apogee of 735 km at approximately local midnight. The payload had a full complement of electrostatic particle detectors but no wave receiver. The proton spectrometer (0.09-23 keV/q) observed both a downflowing isotropic energetic (several keV) ion population and a separate lower energy population of ions whose flux peaked at 90-110° pitch angle. These two populations were not seen to correlate with each other. The second population (90-110° p.a.), found above 400 km altitude and referred to as an acceleration region by the authors, was detected to exist out to 500 eV/q. Yau et al. showed that when the phase space density from various times of this population was plotted, a source region of 400-500 km was found for most of the events. In addition the characteristic energy of these events increased with source altitude. The authors interpreted the increase of characteristic energy with source altitude as being caused by an energy loss at lower altitudes due to ion-neutral collisions in an ion cyclotron acceleration model (this model will be further discussed in the following paragraphs).

The thermal ion instrument (0.1-5.9 eV/q) was used to determine several of the plasma characteristics during the flight. The first of the plasma parameters presented was the ion temperature. Yau et al. argue that there is an absence of significant bulk ion heating in this data, remaining roughly in the kT = 0.14 eV range. However the authors do point out that the temperature is only from those times when the instrument was looking into the rammed plasma. This limited view has the effect of corresponding the up and downleg portions to
while the temperature at apogee would be $T_{\parallel\parallel}$. Also it must be pointed out that the plot of the ion temperature consist of only six data points (not uniformly spaced in time) over the entire duration of the flight. The authors go on to compare the phase space distribution functions of the parallel and perpendicular directions for times when the payload is below, inside, and above their defined acceleration region. These plots show that for both the perpendicular and parallel data below the acceleration region, as well as the two remaining parallel plots, the spectra fall off exponentially beyond the peak as expected from a cold rammed Maxwellian plasma. Furthermore the data from the perpendicular direction inside and above the acceleration region show an elevated high-energy tail. They go on to state that the Maxwellian fit inside the acceleration region yield unreasonably large temperatures and are therefore discounted (and thus explain the lack of data in their ion temperature plot). The other plasma parameter found from the Maxwellian fits of the thermal ion data was the drift velocities. A small parallel drift of $v_{||} = 80 \pm 300$ m/s (large uncertainty due to vehicle motion) was found while the perpendicular drift was found to be between 0.5 and 1.0 km/s. The inferred perpendicular electric field from this drift speed was between 25 and 50 mV/m.

The precipitating electrons were measured by an onboard electron spectrometer (0.08-20 keV range). Strong field-aligned enhancements of the electrons precipitating at the edge of the auroral arcs were seen. No correlation between these field-aligned electrons and the transversely accelerated ions could be made by the authors but they hastened to point out that the electrons did have poor temporal coverage. The electron density (measured by a Langmuir probe) was seen to drop by two decades when the payload entered the acceleration region. The spectral analysis of these density fluctuations revealed a Fourier component at 5.5 Hz which was tentatively identified as a Doppler-shifted $O^+$ ion cyclotron fundamental.

The second sounding rocket flight reported by Yau et al. was IVB-36 which was launched from Churchill, Canada at post-midnight local time and reached an apogee of 585 km. This flight had a similar complement of particle detectors as flight IVB-33 with the addition of wave receivers aboard capable of resolving 30 Hz to 14 MHz. As in the earlier flight, flight IVB-36 observed two distinct ion populations. The energetic ions (>keV) were detected in two different regions during the flight. The first region had a hard
spectrum which peaked near 8 keV while the second region was softer with no significant energy peak. A second ion population primarily at 90° pitch angle was observed while the payload was above 520 km altitude. The authors reported that these ions were seen up to 300 eV but no phase space density or estimation of a source region is given.

The only results reported from the thermal ion spectrometer was an overview of the ion temperature. The authors found that while the payload was above 400 km altitude $kT_i \sim 0.17$ eV while $kT_i \sim 0.14$ eV for altitudes less then 400 km. These results were similar to flight IVB-33 where they also reported no significant bulk heating. Once again it should be noted that due to the nature of the thermal ion spectrometer the ion temperature was calculated only for times when the detector was looking in the rammed plasma. This therefore implies that the up and downlegs sampled the ion temperature in the parallel direction while at apogee the perpendicular direction was sampled.

Flight IVB-36 also observed two regions of intense electron precipitation. Field-aligned electrons were seen in both regions but as was the case in flight IVB-33, no correlation with the transverse acceleration of ions could be made. The electron density was observed to depress by a factor of approximately two when in the acceleration region. The power spectra of the electron density fluctuations for below and inside the acceleration region as well as at apogee were presented for comparison. Inside the acceleration region Fourier components were found at 15 Hz and 45 Hz. During the other two times the 45 Hz component was missing but the 15 Hz component is present with its power being roughly one decade smaller. Yau et al. speculate that the 15 Hz component is the Doppler shifted $O^+$ ion cyclotron fundamental and thus the 45 Hz component would be the n=3 harmonic.

The wave receivers detected both high frequency and low frequency waves during the flight. However none of the waves had amplitudes large enough to provide ion acceleration. The authors did stipulate that if the very low frequency waves (30-500 Hz) observed had their power concentrated in the cyclotron harmonics and were resonant with the ions then the observed rms amplitudes of a few millivolts per meter would be adequate for ion acceleration.

**Associated Theoretical Models**

**Elevated Ion Conics.** Klumpar et al. [1984] first reported the existence of an elevated ion conics. An elevated ion conic has the phase space features of being extended
in the perpendicular direction (similar to a normal conic) and having some nonzero minimum upward parallel velocity component. The distribution is distinctly different from a regular conic in that the outer envelope of the distribution is "bowl" shaped [Horwitz 1986] instead of cone shaped (reasons for this are given in the following paragraphs). This original report brought on a flurry of theoretical explanations for it existence.

Klumpar et al. [1984] have shown examples of elevated conics observed by the energetic ion composition spectrometer aboard DE-1 at altitudes of approximately 22,000 km. In both examples presented, the elevated conic signature was seen in both the O$^+$ and H$^+$ channels. However, in the first example the H$^+$ elevated conic was masked by the presence of intense ambient population and could not be seen directly in the spectrograms. The O$^+$ component is shown to have a low energy field-aligned component which cuts off at 350 eV and has gradually increasing pitch angles to the energetic limit of 5 keV. To explain this hybrid conical distribution, the authors proposed a two stage (bimodal) acceleration mechanism. An ion population is first heated mainly transverse to the local magnetic field at some lower altitude. This distribution is then adiabatically transported up the magnetic field line. During this transport, it encounters a parallel electric field which accelerates the particles and establishes the low energy cutoff.

Klumpar et al. support this position by using a series of arguments from their data. The authors first show that the high energy part of the distribution can be used to determine the size and location of the source region. Using the method in which they assume that the high energy ions received a majority of their energy transversely, the source region can be found from finding the magnetic mirroring point via:

$$\frac{B_0}{B_1} = \frac{\sin^2 \alpha_0}{\sin^2 \alpha_1} = \frac{1}{\sin^2 \alpha_1}, \quad \text{Eqn 1-2}$$

where $B$ is the magnetic field strength, $\alpha$ is the particle pitch angle, and the subscripts 0 and 1 refer to the source and observation points respectively. Furthermore, the size of the source region was estimated by using equation 1-2 and the angular spread of the flux in one of the high energy bins. Thus Klumpar et al. were able to estimate the source region to be centered at approximately 18,000 km and have height of no more than 5,000 km in altitude.
The authors go on to show that when the elevated conic's phase space distribution is plotted, a large gradient is seen in the lower boundary of the distribution for values near zero perpendicular velocity. This gradient is absent at the similar upper boundary and is indicative of an electrostatic acceleration parallel to the magnetic field. They further show that when this distribution was mapped back through a parallel potential of 310 V and then adiabatically back to the center of the source region the resultant is very similar to the transversely accelerated event discussed by Kintner and Gorney [1984]. This distribution was found to have distinct perpendicular (1.17 keV) and parallel (0.26 keV) temperatures. The existence of two separate well-fitted temperatures is indicative of a bi-Maxwellian distribution. Thus it is probable that the elevated conics were produced via a two stage mechanism in which ions were transversely heated to form a bi-Maxwellian distribution and had their parallel velocity elevated from a parallel electric field. The authors do point out that from the equations of motion:

\[ v_{1\parallel}^2 = v_{0\parallel}^2 + \left(1 - \frac{B_1}{B_0}\right) + \frac{2e\phi}{m} , \]  
\[ v_{1\perp}^2 = \frac{B_1}{B_0} v_{0\perp}^2 , \]

that the effects of two types of particle transport are totally commutative and that the data presented has no way of distinguishing which process would have been first.

Horwitz [1984] has shown that the two-dimensional dynamics of a velocity filter mechanism will produce elevated ion conics. The author defines a phase space particle distribution at a given source location in the two-dimensional meridional plane of the magnetosphere and then uses a set of local electric and magnetic field parameters to determine the particle trajectories to the observation location via an integration. Horwitz argues that this model can work for two separate geometries, a latitudinal or longitudinal velocity filter. Figure 1-1 is taken from Horwitz [1984] and shows these two geometries. In either case the author requires a restricted transverse heating region in the direction of plasma convection. In the first example presented (latitudinal velocity filter), Horwitz gives the source region as having a perpendicular electric field of 100 mV/m and a restricted latitudinal range of 66-67.5° (as compared to the two stage scenario proposed by Klumpar.
SCHEMATIC GEOMETRIES FOR VELOCITY - FILTER MECHANISM PRODUCING ION BOWL DISTRIBUTIONS

LATITUDINAL VELOCITY FILTER

HIGH-ENERGY/SMALL \( \alpha \) IONS "OVERSHOOT"

LOW-ENERGY/ LARGE \( \alpha \) IONS "UNDERSHOOT"

TRANSVERSE HEATING IN LATITUDINALLY - RESTRICTED REGION

CONVECTION LATITUDINAL

LONGITUDINAL VELOCITY FILTER

TRaverse HEATING IN LONGITUDINALLY - RESTRICTED REGION

CONVECTION LONGITUDINAL

Figure 1-1
et al. [1984] which requires a broad latitudinal source range of 55-75°). The author then argues that only ions with a limited range of energies and pitch angles will reach the observation location because those with too small average parallel velocity will not make it to the observation region and those with too large average parallel velocity will have already passed through the observation region. Horwitz is able to show in the several cases presented that the computer simulation of the particle trajectories form a "bowl" distribution from this velocity filter. However, the author does point out that while the shape of the outer boundary of elevated conics produced bimodally and by a velocity filter are similar, the distribution within these boundaries are very different. Horwitz points out that the identification of which mechanism produced the elevated conics can be determined by comparison of simultaneously observed $H^+$ and $O^+$ distributions. In the case of the bimodal process, the low energy field-aligned particles of both species receive the same amount of energy from the parallel electric field. In contrast, the velocity filter mechanism imparts the same amount of velocity to the low energy field-aligned $H^+$ and $O^+$ ions. Thus this simple comparison should reveal which process produced the elevated ion conic.

A third model for the production of elevated ion conics was proposed by Temerin [1986]. In this model the author argues that the bowl shaped distribution is just the product of transverse heating of ions along auroral magnetic field lines over an extended altitude range. In this simulation the test particle are started in the ionosphere and are then given a random additional perpendicular velocity kick every time step. The random velocities are drawn from a Gaussian distribution. The parallel motion is strictly determined from the magnetic mirroring force:

$$\dot{v}_\parallel = \left( \frac{v^2}{2B} \right) \frac{dB}{dr}$$  \hspace{1cm} \text{Eqn 1-5}$$

where $r$ is the coordinate along the magnetic field line. To compare this model with the results presented by Klumpar et al. [1984], Temerin presented a test case in which $O^+$ ions of initial temperature of 1 eV were injected at a geocentric altitude of 20,000 km. The particles were allowed to remain in a heating region until they reached an altitude of 28,000 km. In the heating region the random perpendicular velocity kicks they received increased
linearly with altitude. At this point the simulated distribution of Temerin is shown to have similar perpendicular and parallel temperatures, low energy cutoff, and angle of conic as that seen by Klumpar et al. [1984]. Temerin argues that this acceleration is a stochastic process in which ions can gain or lose perpendicular energy at a single time throughout the trip up the heating region. However all during this time the ion distribution is gaining energy and for those times when the perpendicular energy is significant, the parallel energy is also raised due to the magnetic mirroring force. To further prove his point, the author shows the difference in particle distributions produced by heating regions which varied in overall height but retained the same total heating rate. This comparison found that the minimum energy of the field-aligned ions and their parallel temperatures was increased as the size of the heating region increased. Temerin argues that this effect would help explain the nonexistence of reports of elevated conics at lower altitudes (like those observations discussed earlier e.g. Klumpar [1979] and Yau et al. [1983]) and that this would further shown by better low energy resolution of conics at intermediate altitudes. Finally, Temerin states that this model clearly points out that the mechanism for producing conics must heat the bulk distribution and not just the high-energy tail and that this mechanism does not have to occur solely at regions where 90° conics are found (as was the criteria in the study by Kintner and Gorney [1984]).

**Transverse Ion Energization Theories.** Three basic theories have been proposed for the transfer of plasma wave energy to transverse particle energy. Chang et al. [1986] put forth the idea of oxygen ions being accelerated through cyclotron resonance with broad band left-hand polarized waves. The transverse energization occurs when the Doppler-shifted frequency of the broadband electromagnetic ion cyclotron waves match the local gyrofrequency of the ion. This infusion of perpendicular energy will in turn cause the ion to drift up the magnetic field line due to the mirroring force. As the particle travels up the field line, it will be further energized by those electromagnetic ion cyclotron waves who are in local resonance with it. Chang et al. state that the heating should continue while the local wave intensity remains moderately strong ($10^{-8}$ to $10^{-6}$ $V^2/m^2$ Hz).

In discussing the transfer of energy from the electromagnetic ion cyclotron waves to the particle, Chang et al. has shown that when a wave's Doppler-shifted frequency equals the ion gyrofrequency:
where \( q \) and \( m \) are the ion’s mass and charge respectively, then the net increase of the perpendicular velocity for time \( \Delta t \) is:

\[
\Delta v_\perp = \frac{qE_\perp}{m} \Delta t ,
\]

where \( E_\perp \) is the perpendicular electric field of the left-hand polarized wave. In the case of a gyrotropic distribution, each particle pair would then increase its perpendicular energy by:

\[
\Delta W_{\perp, \text{res}} = \frac{q^2E_\perp^2}{2m} (\Delta t)^2 .
\]

Furthermore the authors show that if the perpendicular electric field is identified as:

\[
E_\perp^2 = \Sigma(f_c(l),l) \Delta f ,
\]

where \( \Sigma(f,l) \) is the wave electric field spectral density (a spectral analysis of the electric field which yields power per unit frequency) for a frequency \( f \) at a location \( l \) along the geomagnetic field line and \( \Delta f \) is some bandwidth, then the net heating rate per ion can then be estimated by:

\[
\dot{W}_{\perp, \text{res}} = q^2 \frac{\Sigma(f_c(l),l)}{2m} ,
\]

where \( \Sigma(f,l) \) is taken to be smooth, \( \Delta f \Delta t \approx 1 \), and the dot denotes time differentiation. Chang et al. then use this result as a perturbation of a particles orbit when traveling up a field line in the guiding center approximation. In order to do this simulation the low frequency electric field energy density spectra is approximated by:
\[ \Sigma(f) = \Sigma_0 \left(\frac{f_0}{f}\right)^\alpha, \]  

Eqn 1-11

where \( \alpha \) is a fitting parameter and \( \Sigma_0(f_0) \) is the observed electric field spectral density value at the ion gyrofrequency at that reference geocentric altitude. Chang et al. show that for the parameters \( \alpha = 2.2, f_0 = 45 \) Hz, \( \Sigma_0 = 2.2 \times 10^{-8} \text{ V}^2/\text{m}^2/\text{Hz} \), and an initial energy of 0.25 eV injected at 1.2 RE, the perpendicular and parallel energies reach 62 eV and 38 eV respectively at an observation altitude of 2.0 RE when it is assumed that the low frequency electric field spectral density is comprised of 12% left-hand polarized electromagnetic waves.

A second theory of transverse energization of ions has been proposed by Okuda and Ashour-Abdalla [1983] in which the primary mechanism is heating of the ions by ion cyclotron turbulence. In this model the presence of a continuous flow of cold drifting Maxwellian electrons upwards from the bottomside ionosphere causes the excitement of ion cyclotron waves. The continuous injection of drifting electrons inhibits the formation of a plateau on the electron distribution. This electron flux is maintained by an assumed small dc electric field along the magnetic field. Okuda and Ashour-Abdalla use linear theory to show that for near the fundamental harmonic, \( \omega = \Omega_i \), the real part of the dispersion relation for anisotropic bi-Maxwellian ions and drifting electrons along a uniform external magnetic field reduces to:

\[ \frac{\omega - \Omega_i}{\Omega_i} = \frac{T_{\parallel i}}{T_{\perp i}} \frac{T_{\parallel e}}{T_{\parallel i}} \frac{\Gamma_1}{T_{\perp i}}, \]  

Eqn 1-12

for \( T_{\parallel i}/T_{\perp i} < 1 \) and where \( T \) is the respective temperature of its indicated subscript and \( \Gamma_1 = \exp(-\mu_i) I_1(\mu_i) \), with \( \mu_i = \sqrt{2T_{\parallel i}/m_i} \) and \( I_1 \) being the modified Bessel function of order one. This implies that as \( T_{\parallel i}/T_{\perp i} \) decreases the real part of \( \omega \) will approach \( \Omega_i \) for a given \( \Gamma_1 \) and \( T_{\parallel e}/T_{\parallel i} \). When the ions see a wave whose Doppler-shifted frequency is at its gyrofrequency, then the ion will be accelerated and the wave will be damped. This phenomena is known as cyclotron damping [p.114 Nicholson 1983]. Because the electrostatic cyclotron wave fields are perpendicular to the magnetic field, the ion are thus
heated in that direction. This perpendicular heating continues until the instability saturates due to the ion temperature anisotropy becoming large enough to cause the system to be marginally stable for a given electron drift speed. The critical electron drift speed needed to excite the ion cyclotron waves must also increase as the ion temperature anisotropy grows. When the fundamental harmonic is assumed as the dominate mode, the authors have calculated the maximum ion temperature anisotropy from linear theory to be:

\[
\frac{dT_{\perp i}}{dT_{\parallel i}} \approx \frac{\Omega_i}{\omega - \Omega_i} = \frac{1 + T_i/T_e}{\Gamma_i} \sim 10
\]

Eqn 1-13

To further show the properties of ion cyclotron turbulence heating, Okuda and Ashour-Abdalla have presented results of a computer simulation of their constant flux model. This simulation showed that for \( v_{de}/v_{te} = 1.4 \), where \( v_{de} \) is the electron drift speed and \( v_{te} \) is the electron thermal speed, large amplitude ion cyclotron waves propagate to higher altitudes along the auroral field lines establishing a finite heating region. The ion temperature anisotropy found for this case agreed with the theory, \( T_{\perp i}/T_{\parallel i} \sim 10 \), and it was shown that a larger ion flux was heated as the ion cyclotron waves propagated to higher altitudes. Finally, Okuda and Ashour-Abdalla have shown that in this model a high-energy tail is formed during this acceleration process which has a perpendicular temperature 50-100 times its original temperature.

Transverse ion acceleration by lower hybrid waves (Chang and Coppi [1981], Retterer et al. [1986]) has been proposed. In this theory the positive slope of the electron distributions can excite a sequence of electrostatic modes. The modes in the lower hybrid frequency range have phase velocities equal to the velocities of ions in a high energy tail of the ion distribution. Thus these ions will interact strongly with the lower hybrid frequency waves. Ions with velocities slightly greater than the phase velocity will be slowed down by the wave's electric field and give up energy to the wave while those ions with slightly lower velocities will gain energy. Because ion distributions in the aurora are such that they fall off with increasing velocity (less ions at higher velocities) the ions would overall gain energy and the wave would lose energy. This process is know as Landau damping. Because the electric field in the lower hybrid wave is nearly aligned with \( k \), which is almost
perpendicular to the magnetic field, the ions would be Landau resonated mainly in the perpendicular direction. However, because of the nature of the Landau resonance, this mechanism can only produce an elevated high energy tail and not any bulk heating.

The production of transversely accelerated ions from oblique double layers has also be proposed (Borovsky [1984], Greenspan [1984]). An auroral double layer is defined as two dimensional potential structures tilted from the magnetic field by an angle $\theta$ and having scale sizes of a few tens of kilometers (Borovsky [1984]). The authors propose to show the effects on ion trajectories due to their passage through oblique double layers by running test particle through computer simulation of such situations. Borovsky is further concerned with showing whether the initial properties of the ions determine if the particles are aligned with the local magnetic or electric field after passage through an oblique double layer.

Borovsky was particularly interested in the effects of oblique double layers on ion trajectories in the auroral zone. As an example, Borovsky applied performed a computer simulation using a double layer whose observation had been reported by Mozer et al. [1977]. The parameters of the double layers are presented as $E = 0.5 \text{ V/m}$, $\Delta l = 800 \text{ m}$, $B = 0.072 \text{ G}$, and $\theta = 60^\circ$. The author shows the resulting effects on $H^+$ and $O^+$ for three initial parallel energies (0, 100, and 500 eV). In all three cases the $O^+$ distribution was conical after exiting the oblique double layer while the $H^+$ exhibited this behavior only for the case of highest initial parallel energy. Borovsky also states that the observations of affects on ion trajectories due to their passage through oblique double layers is hindered by the limited pitch angle resolution of a satellite passing through such a small structure. The author further hypothesizes that in the cases when ion conics are seen over an extended region, the probable explanation is that it is simply a case of a series of neighboring two-dimensional double layers which are all conducive to the production of conical distributions. Furthermore, in his discussion section, Borovsky states that in his numerical simulation, electrostatic ion cyclotron waves are sometimes observed adjacent to oblique double layers. The author then points out that in these simulation the particle distributions became more field-aligned as the ion cyclotron wave amplitude grew. He therefore concluded that the ion cyclotron waves were a by product of ion conic production via acceleration by oblique double layers.
Flight Overview

Mission Objective

NASA flight 35.017 was the second flight of the Topside Probe of the Auroral Zone (Topaz) campaign. The flight was proposed to provide a platform at the topside of the auroral ionosphere from which a study of anisotropic ion heating could be performed. This heating contributes greatly to the amount and type of terrestrial ions escaping into the magnetosphere. The four main questions this experiment sought to answer were:

1. What is the mechanism for producing transversely heated ions.
2. What wave modes are generated in heating regions.
3. How do the thermal ions evolve in the heating region.
4. Is there any mass dependence in the heating process.

The instrumentation on board this flight would gather information for a more thorough examination of this region and help answer those questions which were posed.

Payload Configuration and Instrumentation

NASA flight 35.017 was designed to measure the ion fluxes and related phenomena at an apogee of roughly 1000 kilometer altitude. The rocket motor package chosen to reach this high altitude was a Black Brant X. Figure 1-2 shows the three stage Black Brant X and its structure for flight 35.017. The three rocket motors which make up the Black Brant X are the Terrier, Black Brant, and Nihka. In order to insure the payload remained stable during the flight, the spent third stage Nihka motor remained attached for the duration of the flight. Thus the platform from which the TOPAZ II measurements were made was 12.78' in length and 17.26" in diameter. The configuration of the payload after nose cone ejection and instrument deployment is shown in figure 1-3 and includes the experiment section, the telemetry section (TM), the ignition system, the Nihka motor case, and the Nihka tailcan.

The instrumentation for the TOPAZ II rocket was provided by the University of New Hampshire, Cornell University, Marshall Space Flight Center, and NASA's Wallops Flight Facility. An illustration of the payload is given in figure 1-4. The drawing is oriented in
NASA SOUNDING ROCKET
35.017

0"

Experiment Section

58"

TM Sect.

74"

3rd Stage

Nihka

17.26" Dia.

174"

2nd Stage

Black Brant VC

1st Stage

Terrier

Figure 1-2
35.017 Flight Configuration

Experiment Section

TM Section
Ignition System

Nihka Motor Case

Nikha Tailcan

Figure 1-3
35.017 PAYLOAD INSTRUMENTATION

Figure 1-4
the pitch angle coordinate system with the wiring raceways (RW) labeled as the four major azimuthal reference points (0°, 90°, 180°, and 270°). A discussion of the different coordinate systems used for the various applications on this flight is given in Appendix B.

Wallop Flight Facility provided the necessary housekeeping instrumentation which included the on board three axis magnetometer and the horizon sensor. The data from these two instruments were used in combination with the rocket's trajectory and a magnetic field model to determine the payload's aspect for the flight.

The University of New Hampshire provided the particle detection package which measured energetic electrons and ions ranging in energies from 1 eV to 20 keV. The electrons were measured by two cylindrical electrostatic analysers (CESAs). The CESAs provide an accurate picture of the electron precipitation using a narrow field of view (~2.5° look angle) through their 90° cylindrical analyser plates and a rapid (230 msec) energy sweep. The CESAs were swept concurrently from 0 to 20 keV using a 64 step parabolic energy sweep. CESA 1 was mounted with a look direction of 30° from the spin axis while CESA 2 was inclined 60° from the spin axis. The CESAs were thus able to scan the pitch angle ranges of 0-60° for CESA 1 and 30-90° for CESA 2 due to the roughly 30° tilt of the spin axis of the rocket from the magnetic field. It must be noted that the CESAs could only detect the downward precipitating electron and could not detect any return electron flowing out of the ionosphere.

The energetic ions were measured by two octospheric (electrodes are 1/8 of a sphere) electrostatic analysers (OCTO). The OCTOs sampled the energetic ion environment using a large geometry factor (~10^-3 cm^2-sr-keV/keV) and a quick (230 msecs) energy sweep. The OCTOs were swept simultaneously from 0 to 16 keV/q using a 64 step exponential energy sweep. The OCTOs feature a large field of view, 8° x 8°, and an energy per charge resolution of ~10%. OCTO 1 was mounted at an angle of 60° from the spin axis allowing it to sweep out pitch angles between 30° and 90°. OCTO 2 looked down, mounted at an angle of 120° from the spin axis and sampled pitch angles from 90° to 150°. This orientation of the OCTOs allowed for simultaneous coverage of uplooking and downlooking pitch angles.

The thermal ions were investigated using two capped electrostatic hemispherical analysers (CHA). The CHA is a unique electrostatic analyzer because it accepts particles
from a plane and subsequently images their entrance position using a microchannel plate
counter multiplier and a resistive anode strip. An extensive discussion of the design and
testing of the CHA can be found in Pollock [1986] and in the data reduction techniques part
of this thesis. Unlike the previous described pairs of detectors the CHAs flown on 35.017
were not identical. The CHAs were named HEEPS High (HH) and HEEPS Low (HL)
referring to their energy sweeps. HH was exponentially swept in energy from 0 to 755 eV
every 930 milliseconds using 32 steps and had a total instrumental geometry factor of 5 x
ten to the power of -3 cm²-sr-keV/keV. HL was also exponentially swept from 0 to 22 eV in 930
milliseconds in 32 steps. However the start of the two sweeps was offset by one energy
step (28.8 msecs) with HL lagging HH. In order to help avoid saturation of the imaging
HL had a smaller total instrumental geometry factor of 1 x ten to the power of -3 cm²-sr-keV/keV. The
HEEPs were mounted on opposite sides of the payload such that when deployed their
acceptance plane contained the spin axis. The planar acceptance aperture and high speed
energy sweep in combination with the spin rate of ~0.7 Hz allowed for the sampling of the
entire velocity space every 2.765 seconds. It must be pointed out that the geometry factors
quoted for the HEEPS is for instrument as a whole. When comparing the geometry factor
of a detector like the OCTO to the HEEPS, the comparison must be between the OCTO’s
geometry factor and the HEEPS individual bin geometry which is roughly two orders of
magnitude smaller than the overall HEEPS geometry factor. A further discussion of the
determination of the single bin geometry factors and the other properties of HEEPS High
and Low will be presented in the following section on data reduction techniques. A
summary of the basic properties of New Hampshire’s particle package is given in table 1-1.

To supplement the thermal ion measurements made by the HEEPS, Marshall Space
Flight Center (Dr. Tom Moore) provided the SuperThermal Ion Composition Spectrometer
(STICS). The STICS instrument is able to perform three dimensional plasma analysis by
combining a scanning electrostatic analyzer with a magnetic mass spectrometer. The
angular scan enables the STICS instrument to have look direction of ±70° from its nominal
pointing direction, which was normal to the spin axis for flight 35.017. The STICS
electrostatic analyzer front end swept energy from 0.1 to 100 eV while its magnetic sector
separated the ion species into two mass peaks which differ by a factor of 4 in units of
amu/q. The choice of mass selection was swept such that H⁺, He⁺, O⁺, and NO⁺ were
accepted. The total time for a full three dimensional phase space distribution for the STICS
### NASA FLIGHT 35.017 PARTICLE PACKAGE

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<thead>
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<th>Particle</th>
<th>Pitch Angle</th>
<th>Type</th>
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<td>Parabolic</td>
<td>0-20 keV</td>
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<tr>
<td>CESA 2</td>
<td>Electrons</td>
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<td>Parabolic</td>
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<td>Ions</td>
<td>30-90°</td>
<td>Exponential</td>
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<td>230 msecs</td>
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<td>90-150°</td>
<td>Exponential</td>
<td>0-16.5 keV</td>
<td>230 msecs</td>
</tr>
<tr>
<td>Heeps Lo</td>
<td>Ions</td>
<td>All</td>
<td>Exponential</td>
<td>0-22 eV</td>
<td>920 msecs</td>
</tr>
<tr>
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<td>All</td>
<td>Exponential</td>
<td>0-755 eV</td>
<td>920 msecs</td>
</tr>
</tbody>
</table>

Table 1-1
instrument was 10 seconds. The STICS instrument is able to complement the higher time resolution HEEPS instrument by providing the HEEPS with the needed mass compositions.

Electric field measurements associated with ion wave modes (DC to 40 kHz) and electron wave modes (3 MHz minimum) were performed by field experiments provided by Cornell University (Professor Paul Kintner). To cover this extended range of frequencies three kinds of electric field sensors were employed. A 5.5 meter Weitzman boom system was used to sense from DC to 32 kHz by measuring the potential difference between the two spheres at the tips of the booms. The stacer elements of the Weitzman booms were used to detect the high frequency electric fields from 50 kHz to 5 MHz. When deployed the Weitzman boom was perpendicular to the spin axis. The third system used was a Maynard boom set with two sphere pairs. The Maynard boom measured signals from DC to 12 kHz. The Maynard booms were mounted perpendicular to both the Weitzman booms and the spin axis. A single axis search coil was also mounted parallel to the Maynard boom set. The search coil could sense magnetic signals from 30 Hz to 12 kHz. A thorough discussion of the methods of measuring plasma waves and instrumentation used is given in LaBelle and Kintner [1989].

Geophysical Data

Geophysical data for times during the flight was provided by the University of Alaska's magnetometer chain and from the magnetometer on board the GOES 7 satellite (at geosynchronous orbit). Figure 1-5 shows these two data sets for time periods which include the rocket flight. The GOES 7 satellite data (top panel of figure 1-5) shows the typical signature of the onset of an auroral substorm. The data traces shown represent the magnetic field strength: along the geomagnetic axis (HP - polar signal), towards the earth (HE - earthward), and normal to the previous two axis (HN - normal). The HP signal is seen to decrease slightly after 05:00 UT while at the same time the HE component is on the rise. Following this stretching phase of the magnetic field, the substorm is launched via the relaxation of the magnetic field. This is seen as the sudden rise of the HP component at shortly after 06:00 UT and is accompanied by a decrease in the HE signal.

The bottom panel of figure 1-5 shows the response of the University of Alaska's
Figure 1-5

GOES-7 Magnetometer

Alaska Magnetometer Chain H-trace

Hours (UT) 19 January 1988
magnetometer chain to the arrival of this substorm. The stations listed go from the southern most station of Talkeetna (TLK, $\Lambda = 63.0^\circ$) to the northern most station of Sachs Harbour (SAH, $\Lambda = 75.2^\circ$). Shortly before launch (the period of flight is marked on the figure by the two dashed vertical lines prior to 09) the magnetic $H$ component is seen to have a large negative bay in the Fort Yukon (FYU, $\Lambda = 66.8^\circ$) and Arctic Village (AVI, $\Lambda = 68.1^\circ$) signals. This is indicative of a westward electrojet current system flowing in the ionosphere above those sites. This negative bay is seen to appear in the three most northern stations at the time of launch. This fortuitously meant that the auroral arcs were traveling in the same northward direction as the path of the rocket. This enabled the rocket to travel through a almost continuous presence of precipitating auroral electrons.

**Flight Plan and Vehicle Performance**

The success of a suborbital scientific mission is largely dependent on the performance of the launch vehicle. Prior to the launch of 35.017, performance standards for the flight were set in accordance with the desired science goals. The three areas of concern were minimum altitude of apogee, payload stability, and spin rate of the rocket. To reach the topside of the ionosphere where ion heating is prevalent, it was set forth that the payload have an optimal altitude of 900 km at apogee, with a minimum acceptable apogee of 725 km. The previous TOPAZ flight had proven to be dynamically unstable, thus constraints were placed on the coning half-angle, cone rate, and payload alignment with respect to the magnetic field. The coning half-angle was not to exceed 45° and the ratio of the coning rate to the spin rate was not to exceed 0.1. To insure complete coverage of the precipitating particles the angle between the payload spin axis and the magnetic field was not to exceed 60°. Finally, the rocket was required to be despun to 1 Hz before deployment of the Maynard booms to reduce the amount of torque applied on them.

The schedule of predicted events for flight 35.017 is given in table 1-2. The actual sequence of events nominally followed the predicted schedule with slight differences in the altitude and rocket velocity, as can be seen in figure 1-6. Flight 35.017 easily met all of the vehicle performance criteria that had been set out before launch. Careful examination of figure 1-6 shows that the payload eclipsed the optimum altitude by reaching an apogee altitude of 927 km. Furthermore, the payload prove to be quite dynamically stable for the
35.017
SCHEDULED
FLIGHT EVENTS

<table>
<thead>
<tr>
<th>Event</th>
<th>Nominal Altitude (km)</th>
<th>Nominal Time (sec)</th>
</tr>
</thead>
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<tr>
<td>Terrier Ignition</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Terrier Burnout</td>
<td>1.1</td>
<td>4.4</td>
</tr>
<tr>
<td>Black Brant Ignition</td>
<td>3.8</td>
<td>12.0</td>
</tr>
<tr>
<td>Black Brant Burnout</td>
<td>35.6</td>
<td>44.4</td>
</tr>
<tr>
<td>Nihka Separation</td>
<td>79.6</td>
<td>71.0</td>
</tr>
<tr>
<td>Nihka Ignition</td>
<td>85.7</td>
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</tr>
<tr>
<td>Nihka Burnout</td>
<td>129.4</td>
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<td>Despin</td>
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<td>100.0</td>
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<tr>
<td>Nose Cone Deploy</td>
<td>171.8</td>
<td>105.0</td>
</tr>
<tr>
<td>Heeps Deploy</td>
<td>189.2</td>
<td>110.0</td>
</tr>
<tr>
<td>Maynard Boom Deploy</td>
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<td>115.0</td>
</tr>
<tr>
<td>High Voltage Turnon</td>
<td>219.7</td>
<td>119.5</td>
</tr>
<tr>
<td>Weitzmann Boom Deploy</td>
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<td>120.0</td>
</tr>
<tr>
<td>Apogee</td>
<td>927.5</td>
<td>550.8</td>
</tr>
<tr>
<td>Ballistic Impact</td>
<td>0</td>
<td>1044.5</td>
</tr>
</tbody>
</table>

Table 1-2
Payload Altitude and Geomagnetic Velocity

Flight Time (sec)

VMx (km/s)

VMy (km/s)

VMz (km/s)

Altitude (km)

Figure 1-6
entire flight. Table 1-3 shows the spin rate, cone half-angle, and coning rate as determined by Hank Dolben from the calculation of the rocket's aspect. The data listed were determined for the intervals between the times listed. The cone half-angle was a modest $2.1^\circ$ during most of the flight and the ratio of the cone rate to spin rate was approximately 0.05. The spin rate during the Maynard boom deployment, as shown in table 1-3, was 0.725 Hz. The orientation of the payload with respect to the magnetic field also was well within the preset standards. Figure 1-7 shows the how the rocket actually starts with a maximum angle of $35^\circ$ between the spin axis and magnetic field and progressively get more field aligned. With the adequate spin rate and successful nose cone ejection, all of the instruments on 35.017 were deployed.

**Instrument Performance**

NASA flight 35.017 had the fortune of having a 100% success rate for the predicted instrument performance. All of the instruments turned on with activation of high voltage and there was no failure of an instrument during the flight. However it is the unpredicted which can sometimes cause misfortune. During two portions of flight 35.017 the payload was in a region of intense high energy (>10 keV) electron precipitation. The electrons caused the payload to be driven up to -7 V (payload charging is discussed in Appendix B) thus reducing the number of energy steps with which the thermal ions could be sampled. This affect was most acutely seen in the HEEPS Lo where the charging of the rocket made the ions undetectable until the 16th step of the 32 step energy sweep. However this was not a serious problem, just reducing the total amount of workable data.

Another problem encountered during the flight of 35.017 was the presence of false counts due to ultraviolet contamination. The electrostatic particle analysers on board 35.017 used either microchannel plates or channeltrons to detect the presence of charged particles. However, both microchannel plates and channeltrons respond when struck by a ultraviolet photon. Precautions were taken to make the detectors as nonreflective as possible by coating them with the carbon based Aerodag. As mentioned in the previous paragraph, flight 35.017 traveled above two bright active aurora which were intense sources of ultraviolet light. From the pattern of the contamination in the data, roll dependent but no energy dependence and always detected from below the rocket, it was
# 35.017

## ANGULAR INFORMATION

<table>
<thead>
<tr>
<th>Time (Sec)</th>
<th>Spin Rate (rev/sec)</th>
<th>Cone Half-Angle (°)</th>
<th>Cone Rate (rev/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>0.7258</td>
<td>2.5</td>
<td>0.0389</td>
</tr>
<tr>
<td>200</td>
<td>0.7264</td>
<td>2.5</td>
<td>0.0389</td>
</tr>
<tr>
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<td>0.7276</td>
<td>2.5</td>
<td>0.0389</td>
</tr>
<tr>
<td>350</td>
<td>0.7284</td>
<td>2.1</td>
<td>0.0389</td>
</tr>
<tr>
<td>500</td>
<td>0.7286</td>
<td>2.1</td>
<td>0.0389</td>
</tr>
</tbody>
</table>

Table 1-3
Angle Between Payload Spin Axis and Magnetic Field

Figure 1-7
determined to have been caused by the auroral ultraviolet emission. Furthermore none of the up looking electrostatic particle analysers or that section of the HEEPS which was up looking were affected. This again simply meant a reduction of the amount of data there was to work with. The procedure for taking out this contamination will be discussed in the next section. Because of this experience an ultraviolet absorption coating for the electrostatic particle analysers was developed and flown on UNH's last experiment NASA flight 35.020. A detailed discussion of this is given in Section 2 of this thesis.
Data Reduction

In order for the results of scientific experiments to be usable, the means in which the data is gathered must be fully understood. Two major questions which have to be answered are: how is the instrument viewing the particles, and how does the instrument react to these particles. These questions should always be answered by the preflight calibration. In the case of the HEEPS instrument, a much more rigorous routine is required due to its complex nature. Recognizing the inadequacies of calibrating the HEEPS instrument with a point source particle emitter, a new calibration facility was built centered around a broad beam particle gun (discussed in Section 2). However, at the time of the calibration of flight 35.017 this new calibration system was not yet in place. Thus a standardized calibration using techniques developed from previous flight calibrations was employed. To understand these procedures a review of the HEEPS instrument is first required.

Review of the HEEPS Instrument

The HEEPS instrument is the University of New Hampshire's development of a capped hemisphere analyzer first conceived by Dr. C. Carlson [Carlson et al., 1983]. A schematic of the HEEPS is given in figure 1-8. The HEEPS can be broken down into three major sections; the entrance aperture and analyzer plates, the imaging section, and the electronic logic section. The unique feature of the HEEPS instrument is the planar entrance aperture. The entrance aperture is fashioned from the geometry of the three parts which make up the electrostatic analyzer portion of the instrument. These three parts are the top hat, the outer hemisphere, and the inner hemisphere. The transmission properties of the HEEPS are determined by the size and shape of these parts. A lengthy discussion of this and other specific details of the HEEPS instrument can be found in Pollock [1986]. Of importance to one studying the data is the fact that the combination of a planar entrance aperture and the hemispherical analyzer plates allows for the transmission of a particle from a discrete point in the entrance aperture plane to a discrete point on the imaging section.

The imaging section is composed of a pair of microchannel plate electron multipliers
HEEPS SCHEMATIC

Figure 1-8
(MCPs), the annular resistive strip anode, and the charge sensitive pre-amplifier. The MCP gain is limited by ion feedback [Timothy 1981] which can be inhibited by the use of MCPs whose channel axis is not perpendicular to their input or output faces. The MCP pair is then arranged in a chevron configuration (the top and bottom channels combining to form a chevron) for best performance, having an output gain of typically $10^6$ electrons for each ion input. This charge burst is then delivered to the annular resistive strip anode. The resistive strip a carbonized polymer resistive ink applied to a glass laminate such that the strip is centered on the output channel of the electrostatic analyzer plates and forms an arc of $350^\circ$ terminating at ends A and B. Because the different plates of the electrostatic must be mechanically held apart, three "blind" spots spaced $120^\circ$ apart are formed on the imaging anode. The largest of these is located at the termination of the resistive strip and is $40^\circ$ wide. The other two blind spots are roughly $15^\circ$ wide. While the blind spots are a necessary inconvenience, they are easily dealt with using the calibration data. When an charge burst strikes the resistive anode, proportional burst are then delivered to the strip ends A and B. These burst are then amplified by the charge sensitive pre-amplifiers located immediately adjacent to the ends of the resistive anode. The pre-amplifier board then passes on the signal from A, $S_A$, and the sum of the signals, $S_{A+B}$ to the logic board.

The HEEPS electronic logic section decodes the electronic signals sent by the pre-amplifiers to determine the imaging of the event. The method employed by the logic board is known as the resistive charge division. The position of the a charge burst on a resistive strip anode with ends A and B is determined by the equation:

$$\frac{S_A}{S_A + S_B} = \frac{x_0}{L}.$$  
Eqn 1-14

Before calculating the position of the event, the logic board first passes $S_{A+B}$ through a lower level discriminator (LLD) and a upper level discriminator (ULD). The LLD rejects all events which have pulse height distributions below a predetermined noise level. All of the events which are not rejected by the LLD increment the HEEPS Total Counts (HTC) register. The ULD prevents the passage of those events which would overflow the analog to digital converter. Events which do pass both of the LLD and the ULD have $S_A$ and
$S_{A+B}$ input into an analog to digital converter. This chip outputs a 6 bit address from determining the ratio defined in equation 1-14 and then multiplying it by 64. This address represents a bin location on the resistive strip where the strip has a total of 64 bins with each bin being approximately 5° wide (320°/64). The logic microprocessor then increments the counter at that address. At the end of the accumulation period, the images at the 64 addresses are then read into a First In First Out (FIFO) data chip which in turn streams the image serially to the telemetry (TM). The HTC is also read out once per accumulation period.

Because the arrival of the particles to the HEEPS detector is random, the electronics have been compensated to ensure that there is no pulse pileup (the triggering of an event in the middle of the sending of a previous event) in the data. A forced deadtime accomplishes this by not allowing any pulses to the chips for a duration slightly longer than their known process time. The HTC deadtime is just that for a simple counter and requires only 2 µsecs while the angular distribution must be determined by the microprocessor and requires a deadtime of 10 µsecs. The cost of enforcing these deadtimes is a compression of the data which causes the counting rate to be less than the actual event rate. However the event rate can be retrieved via the formula:

$$E_{HTC} = \frac{C_{HTC}}{1 - (C_{HTC} \ast \tau_{HTC})},$$

Eqn 1-15

where $E_{HTC}$ is the total event rate, $C_{HTC}$ is the HTC count rate, and $\tau_{HTC}$ is the 2 µsec forced deadtime. This event rate can be used along with the imaging deadtime ($\tau_{IMG}$) to calculate count rate ($C_{IMG}$) for all of the imaging process via:

$$C_{IMG} = \frac{E_{HTC}}{1 + (E_{HTC} \ast \tau_{IMG})},$$

Eqn 1-16

This counting rate and the total event rate can then be used to calculate the individual accumulation bin event rate ($E_j$) via:
HEEPS Accumulation Bins

A single look direction detector's look angle is easily defined as the angle between look direction and the spin axis of the payload. Defining this individual accumulation bin look angles for a capped hemispherical analyzer is like putting together 64 continuous single look direction detectors. Thus it is important to understand how each of these 64 components relate to one another. Therefore a rigorous method was used to determine the individual look angle of each of the 64 different accumulation bins. The major test of the HEEPS instruments to determine the look angles was the azimuthal angular calibration. The HEEPS was mounted on a rotational feedthrough and allowed to accumulate a fixed number (4000) of HEEPS total counts. The instrument was then rotated five degrees in azimuth (figure 1-9) and this procedure was repeated for the entire azimuthal range of ~330°. The data taken from the HEEPS HI azimuthal angular calibration is shown in the top panel of figure 1-10. The three blind spots are seen as the gaps at 120°, 240°, and the gap between 330° and 10°. Because a fixed number of counts were recorded at every azimuthal step, each azimuthal distribution (i.e. a column in top panel of figure 1-10) can be normalized. Thus the normalized data in a column gives the probability of a bin receiving counts at a fixed azimuthal angle. Therefore the inverse of this is that a row will contain the probability of an azimuthal angle receiving counts in a certain bin. The azimuthal angle with the highest probability for receiving counts was assigned as the look angle for that specific bin. However, a modification must be made because bins on the edges of blind spots are known to be less sensitive (i.e. require more time to acquire a fixed number of counts) than normal bins. This is seen in the bottom panel figure 1-10 which shows accumulation time for each azimuthal step. A prolonged accumulation time will cause more
AZIMUTHAL ANGULAR CALIBRATION

Side View

Energy Charge $\equiv e = V_g$

Vacuum Chamber Wall
Image Data
Rotational Feedthrough

Top View

Blind Spots

Figure 1-9
HEEPS Angular Calibration
(35.017)

HEEPS Angular Accumulation Time
(35.017)

Figure 1-10
counts to be registered in neighboring bins. This will cause a spreading of the normalized angular distribution. When viewed from the fixed bin (single row in top panel of figure 1-10) perspective, this spreading will cause an increase of the probabilities of angles near blindspots. To compensate for this possible angle shifting, the normalized distributions were modified (reduced proportionally to the accumulation time) for those angles which required extra long accumulation times. The mean angle (most probable) for each bin was then computed. However because no data could be gathered in the blindspots, a mean angle could not be determined. Instead the mean look angles were plotted versus bin number and a best fit line was found. From this best fit line the azimuthal angles of the blindspots were found numerically. A schematic of the previous described procedures is given in figure 1-11.

The unique feature of the HEEPS having 64 accumulation bins is that it is comparable to having 64 separate instruments. Because the bins can be thought of as an individual, each bin's geometry factor must be calculated. However before that can be done, the instrument must be examined as a whole. Figure 1-12, taken from Pollock [1987], shows the various dimensions which determine the overall features of a capped hemispherical analyzer. The radius of the inner, outer and cap hemispheres are designated $R_1$, $R_2$, and $R_3$ respectively while the gap between the inner and outer hemisphere ($R_2 - R_1$) is $\Delta_1$. The three truncation angles are known as $\Theta$, $\alpha_{\text{coll}}$ and $\sigma$. Carlson et al. [1983] have computationally and experimentally tested the transmission properties due to variations of these different parameters. The results of these tests are shown in figure 1-13, taken from Carlson et al. [1983]. The plot shows five different transmission properties as a function of a normalized gap spacing ($\Delta_1/R_1$). The quantities shown plotted are: normalized geometry factor ($G/R_1$), the mean of the product of the fractional velocity bandpass ($\Delta v/v$) and the polar angle bandpass ($\Delta \theta$), and the analyzer ratio ($T_{\infty}/qV$) which represents the needed applied voltage across the electrostatic plates in order to select a desired energy per charge particle. Carlson et al. [1983] have expressed all of these quantities in terms of a velocity bandpass. Work with the HEEPS has traditionally used an energy bandpass as a frame of reference. A discussion on the physical meaning of the transmission properties introduced above (but in terms of an energy bandpass) is given in Section II. The geometry factor of the total HEEPS instrument has been shown to be in more conventional
Accumulation Bin Angle Schematic

Azimuthal Calibration Angles

Accumulation Time

Normalized Distribution

Modified Normalized Distribution

Non-Blind Spot Accumulation Bin Angles

Blind Spot Accumulation Bin Angles

Best Fit Line

Accumulation Bin Angles

Figure 1-11
CAPPED HEMISPHERE
ANALYZER

Figure 1-12
units [Pollock 1987]:

\[ G_0 = 2R_1^2 \times \frac{G}{R_1^2}, \]  
Eqn 1-18

where \( R_1 \) is the radius of the inner hemisphere of the HEEPS and \( G/R_1^2 \) is determined from figure 1-13. When the values for the HEEPS flown on flight 35.017 are put into equation 1-18 the geometry factor is found to be

\[ G_0 = 1.944 \times 10^{-2} \text{cm}^2 \text{ster-keV} \text{keV}. \]

If the approximation that the bins are taken as being 5° in angular width (which is a good approximation according to the data taken during the azimuthal angular calibration), then the individual bin geometry factor can be calculated as:

\[ G_{oi} = G_0 \frac{5^\circ}{360^\circ} = 2.70 \times 10^{-4} \text{cm}^2 \text{ster-keV} \text{keV}. \]  
Eqn 1-19

However, because in practice the bins have slightly different sensitivity, \( G_{oi} \) should be modified by a factor determined from the normalized azimuthal distributions which reflects this sensitivity.

Pollock [1987] defines the individual bin geometry factor as:

\[ G_{oi} = A \delta\phi \left( \sin(\theta) \delta\theta \delta\epsilon_e \right), \]  
Eqn 1-20
CAPPED HEMISPHERE DESIGN & TRANSMISSION PARAMETERS

Figure 1-13
where $\delta A$ is the effective area of the entrance aperture, $\delta \phi$ is the azimuthal bandpass width, and $\left\langle \sin(\theta) \delta \theta \frac{\delta \varepsilon}{\varepsilon} \right\rangle$ is the mean value of the product of the contribution of the polar angle to the angular bandpass and the bandpass in energy per charge ($\varepsilon$). A discussion of the physical meaning of these terms and the orientation of the respective angles is given in Section II (see figure 2-27). Pollock was able to define these parameters via extensive calibration of a prototype HEEPS. He was then able to find the bin geometry factor for separate HEEPS by scaling the prototype bin geometry factor using information from the curves from figure 1-13. This method was applied to the HEEPS flown on flight 35.017 as a comparison. The scaling method using the prototype bin geometry factor yields:

$$G_{oi}^{35.017} = A \cdot G_{oi}^{\text{Proto}} = A \left[ 2R_1^2 \times \frac{G}{R_1^2} \right]^{\text{Proto}}$$

$$= \left[A_1 2R_1^2\right]\left[A_2 \frac{G}{R_1^2}\right]$$

Eqn 1-21

where $A_1$ is a scaling due to the differences in $R_1$ and $A_2$ is a scaling due to the differences in $\frac{G}{R_1^2}$. Upon putting in these differences, the scaling factors were found and combined. The bin geometry factor was then calculated to be:

$$G_{oi}^{35.017} = A \cdot G_{oi}^{\text{Proto}} = 29.75 \times \left(2.0 \pm 0.41, 1.40 \pm 0.50\right) \times 10^{-5} \frac{\text{cm}^2\text{-ster-keV}}{\text{keV}}$$

$$= \left(5.95 \pm 1.20, 4.10 \pm 0.41\right) \times 10^{-4} \frac{\text{cm}^2\text{-ster-keV}}{\text{keV}}$$

The lower limit of this value is in agreement with the approximation method previously discussed. Because the two methods gave similar values, the bin geometry factor was set to the value found using the first method and then adjusted for bin sensitivity.

**Heeps Energy Sweeps**

While it is crucial to know from what direction the detected particles are coming from, it is just as essential to know the relationship between the potential being applied across the analyzer's parallel plates and energy per charge being transmitted to the MCP. In order for the HEEPS to sample a predetermined range of velocity space, the voltage across the
HEEPS parallel plates are electronically swept during flight. The electronics package for flight 35.017 had both HEEPS instruments being swept from zero to a maximum value using a 32 step exponential sweep. It was decided that one HEEPS (HL) should stay primarily in the range of thermal ions and that the second (HH) should sweep to energies large enough to detect the presence of any superthermal tail. The calibration procedure to determine the values of the energy steps requires two part test. The HEEPS were fixed such that the ion source was aligned with a non-blindspot area of the detector. The potential across the parallel plates was then held constant (constant energy step) while the ion gun's energy was swept. The second part of the test was just the inverse of the first

<table>
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<tr>
<th>Energy step</th>
<th>$e_{\text{min}}$</th>
<th>$e_{\text{max}}$</th>
<th>$e_{\text{ave}}$</th>
<th>$\Delta V$</th>
<th>$F$</th>
<th>$F_{\text{ave}}$</th>
<th>$E_{\text{max}}$</th>
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Table 1-4

part of the test, the gun was held at a fixed energy and the voltage across the parallel plates was swept. Table 1-4 list the data from the calibration test. The left most column shows the fixed energy step (HI or LO indicating which HEEPS) at which the first part of the test was conducted. The gun energy was swept an the values of the gun energy at the half maximum count rate is listed in the $e_{\text{min}}$ and $e_{\text{max}}$ columns. These two values are used to find the average energy value ($e_{\text{ave}}$) for that step. The second part of the test required setting the ion gun at the average energy value and then finding the applied potential ($\Delta V$) which yielded the maximum count rate. It is then assumed that the energy scales linearly
with the applied potential (i.e. \( \varepsilon_{\text{ave}} = F \Delta V \) where \( F \) is a scaling factor). Thus a scaling factor can then be found for each of the energy steps tested (3 steps for HI and 4 for LO). An average value of \( F \) is then computed and used with the known applied potential to calculate the value of the last step (\( \varepsilon_{\text{last}} = F_{\text{ave}} \Delta V_{\text{last}} \)). The values of the remaining steps are then found from a laboratory program designed to generate the values of exponential energy sweeps given the value of the last step. Table 1-5 list the determined values of the energy sweep steps for HH and HL.

Pollock [1986] has shown that the theoretical value of the relation between the electrostatic potential between two parallel plates and the energy per charge of the particle which can pass through these plates is:

\[
\varepsilon = \frac{m v^2}{q} = \frac{R_0}{R_2 - R_1} \times \frac{V_2 - V_1}{2},
\]

Eqn 1-22

where \( R_0 \) is the radius of the midpoint between the two plates, \( R_1 \) is the radius of the inner plate, \( R_2 \) is the radius of the outer plate, \( V_1 \) is the potential of the inner plate, and \( V_2 \) is the potential of the outer plate. For the two HEEPS on board flight 35.017 the theoretical value yields:

\[
\varepsilon_{\text{HH}} = 3.50 \left( V_2 - V_1 \right) = 3.50 \Delta V,
\]

\[
\varepsilon_{\text{HL}} = 4.81 \left( V_2 - V_1 \right) = 4.81 \Delta V.
\]

Eqn 1-23

This method yields energies within 10% of the calculated value for both HEEPS. This is also within the energy acceptance bandwidth of the HEEPS.

**Coordinate Systems**

With the knowledge of the particle's acceptance energy and angle, the detected velocity vector is then known assuming the mass composition has been determined. However if this vector is expressed in an arbitrary coordinate system it will most likely be useless for any sort of data analysis. As shown in figure 1-4, the deployed HEEPS detectors have the payload spin axis parallel to their acceptance plane. In terms of a rocket coordinate system, referred to as the pitch angle coordinate system, an acceptance bin of the HEEPS would
## HEEPS Energy Sweeps

<table>
<thead>
<tr>
<th>STEP</th>
<th>ENERGY PER UNIT CHARGE (eV/q) HEEPS LOW</th>
<th>HEEPS HIGH</th>
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<tr>
<td>1</td>
<td>0</td>
<td>0</td>
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<tr>
<td>2</td>
<td>0.02</td>
<td>0.8</td>
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<td>1.7</td>
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</tr>
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</tr>
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</tr>
<tr>
<td>32</td>
<td>21.7</td>
<td>755.0</td>
</tr>
</tbody>
</table>

Table 1-5
have a single polar angle \( \theta \) and azimuthal angles \( \phi \) as shown in figure 1-14. The complete set of 64 acceptance bins would vary by approximately 5° in polar angle and have one of two azimuthal angles (depending upon which side of the MagZ axis the bin is located). The on-board magnetometer also read out the measured magnetic field during the flight in this system. Thus the convenience of this coordinate system, and hence its name, is due to the fact that the bin look direction and magnetic field vector can determine the pitch angle (the angle between the particle velocity and magnetic field) of the detected particle via:

\[
\alpha = \arccos \left( \frac{\mathbf{B} \cdot \mathbf{u}_i}{|\mathbf{B}|} \right),
\]

Eqn 1-24

where \( \mathbf{B} \) is the magnetic field vector, \( \mathbf{u}_i \) is the acceptance bin's unit vector, and \( \alpha \) is the pitch angle and can range between 0 and \( \pi \). With the pitch angle \( \alpha \) and the magnitude of the velocity of the detected particle determined, the particle flux can be plotted versus its velocity parallel to the local magnetic field and perpendicular to the local magnetic field. This allows for the easy detection of velocity anisotropies for particle velocities greater than the rocket velocity. However, thermal ion velocities are comparable to the rocket velocity and require a coordinate system in which the ram and antiram data are not folded together.

Along with the a distinct ram (plasma speed in the rocket frame of reference) and antiram direction, a meaningful coordinate system must also include the magnetic field as one axis. The \( \text{nr} \text{b} \) coordinate system is such a system where the unit vectors are defined by

\[
\mathbf{\hat{b}} = \frac{\mathbf{B}}{|\mathbf{B}|},
\]

Eqn 1-25

\[
\mathbf{\hat{n}} = \frac{[\mathbf{V}_r \times \mathbf{B}]}{|\mathbf{B}| |\mathbf{V}_d|},
\]

Eqn 1-26

\[
\mathbf{\hat{r}} = \mathbf{\hat{b}} \times \mathbf{\hat{n}},
\]

Eqn 1-27

where \( \mathbf{B} \) is the magnetic field vector and \( \mathbf{V}_r \) is the plasma ram vector. The \( \text{nr} \text{b} \) coordinate
Pitch Angle Coordinate System

Figure 1-14
system therefore always has the plasma ram in the r-b plane. It should be noted that calculation of this coordinate system required the knowledge of the payload’s translational and rotational motion (i.e. trajectory and aspect). This data was furnished by Hank Dolben (a detailed description is given in Appendix B). The nrb system also is a simple rotation of the Geomagnetic coordinate system. The rocket's trajectory was slightly west of geomagnetic north for the entire flight (see figure 1-15). Therefore the -r axis can be taken as roughly the geomagnetic north when comparing this data to other data reported in a Geomagnetic coordinate system.

**Flight Situations**

During the course of data analysis certain anomalies tend to occur. Many times these problems are readily solved by various methods while others can place restrains on an entire data set. The data set from flight 35.017 has two such constraints. The trajectory of flight 35.017 took the rocket through three discrete arcs of much larger intensity then any other previous University of New Hampshire flight of capped hemispherical analysers had been through. The large openings of the HEEPS instruments were coated with the conducting Aerodag to prevent ultraviolet leakage. However this coating failed to completely absorb the UV radiation. The intense UV emissions from the aurora can be seen as a spin modulated, non-energy dependent signal in the accumulation bins which are looking directly downwards. Because the signal was very strong and the varied in bin space according to position of the bins, it was decided that this data would be removed from the data set. The second anomaly had to due with a syncing of the HEEPS' energy sweep and the spin period of the payload. The HEEPS energy sweep took 0.9216 seconds to complete. When the payload had despun, it had a spin period of 1.372 seconds. This meant that for flight 35.017, there were approximate three energy sweeps for every two payload revolutions. This caused the azimuthal plane in velocity phase space to be sampled at only three set locations over periods of tens of seconds. While this does not contaminate the data, it has been found to hamper greatly any effort to unambiguously identify large plasma flows in the plane perpendicular to the magnetic field.
nrb Coordinate System

time = 350 FT

Figure 1-15
Flight Observations

NASA flight 35.017 was designed to study the evolution of plasma in an auroral structure at the topside ionosphere. As has been discussed in the previous sections, the payload contained a complete wave and particle package. Of particular interest on this flight was the evolution of the thermal ion population during transverse heating events. The UNH package of two capped hemispherical analysers have made unique observation of these particles by being able to rapidly (~1 sec) sample their distribution function. From this distribution function such questions can be answered as: are large velocity drifts seen, is the population isotropic or is a preferred direction of acceleration seen, as well as being able to determine the various plasma parameters. When these question have been answered, this data is then correlated to the other measurements made during the flight.

Electron Observations

While flight 35.017 was primarily interested with making detailed measurements of the observed ions, two electron cylindrical electrostatic analysers (CESAs) were aboard to measure the precipitating auroral electrons. As described in the previous section, the CESAs has a fast energy sweep (~230 msecs) and were arranged such that CESA1 observed electrons with pitch angles between 0-60° and CESA2 between 30-90°. An overview of the observed electrons are seen in figure 1-16. The vertical axis is the energy of the electrons (0-20 keV) and the horizontal axis is the flight time (time after launch). The grayscale in the upper and lower panels represent the respective average count rate observed by CESA1 (top panel) and CESA2 (bottom panel). The count rate goes from zero (white) to $10^{-4}$ counts/second (black). This plot shows that almost immediately after high voltage turn on (119 sec FT) the rocket had entered a discrete auroral arc. At roughly 410 secs FT the payload emerged from the auroral structure and then continued on into a second discrete auroral structure at 460 secs FT. This second auroral structure contained highly energetic electrons whose spectra peaked at energies greater than the highest CESA energy step (19.6 keV). The rocket came briefly out of this auroral structure and then entered in the third auroral structure which was had precipitating electrons with energies up
Figure 1-16

TOPAZ 2

Energy (keV) vs. Flight Time

avg. CESA 1 c sec⁻¹ x 10⁻³

avg. CESA 2 c sec⁻¹ x 10⁻³
to 15 keV. The payload left the arc at 780 secs FT.

The comparison of the top and bottom panels of figure 1-16 show the presence of field-aligned electrons (Arnoldy et. al. 1974) in the auroral arcs. Much of the highest energy electrons in the three arcs are seen to be field-aligned. A low energy (<1.3 keV in figure 1-16) population of field-aligned electron is also present in the first two arcs.

A better understanding of the electron behavior during the times when the field-aligned population is observed can be found by examining the CESA data in finer temporal resolution. Figure 1-17 shows the flight time of 242 to 244 secs (horizontal axis) when the low energy field-aligned electron component is present. The top two panels in figure 1-17 present pitch angle and count rate from CESA1, while the bottom two show the count rate and pitch angle from CESA2. The middle panel is the trace of the energy sweep monitor indicating at what energies the electrons were detected. The energy sweep monitor shown is for low energy resolution and truncates the high energy steps into a false plateau. The existence of a field-aligned burst well below the monoenergetic peak is clearly obvious in this data and has been previously recorded in literature (e. g. Arnoldy 1981). It is also clearly shown in this figure that along with this field-aligned burst, the overall flux of electrons with pitch angles between 0-60° is higher than that between 30-90°. A more dramatic case of this is shown in figure 1-18 (same layout as figure 1-17). As CESA1 is spun through 0° pitch angle, the low energy field-aligned peak is once again present, however there also is a sharp simultaneous enhancement of the electron flux at the monoenergetic peak. The monoenergetic peak is the term for the energy peak of the electron spectrum [Arnoldy 1981]. Because of the large time period and limited pitch angle coverage of the CESA data, the data is not suited for display in a phase space format.

A qualitative description of the downward flowing electron flux is given by comparing the integrated electron energy flux of the two CESAs. The integrated electron energy flux is defined as the electron energy flux through an orientable surface perpendicular to the magnetic field. In terms of measurable quantities, the integrated electron energy flux is;

\[ I_e = \int \frac{1}{2} m v^2 \cdot d^3 v, \]  

Eqn 1-28
Flight Time (0.05 sec/div)

<table>
<thead>
<tr>
<th>Angle (°)</th>
<th>(cts KHz)</th>
<th>Angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

CESA 1
CESA 2

Energy (cts KHz) (keV)

F.A. "Monenergetic"
TOPAZ 2
Integrated Electron Energy Flux

Figure 1-19
where $I_e$ is the integrated electron energy flux, $f(v)$ is the electron single particle distribution function, $1/2 m v^2$ is the electron energy, and $v \cdot d^3v$ is the velocity through the orientable surface perpendicular to the magnetic field. All of these terms can be related to physical parameters measured by the CESAs (see Appendix A for details). The results of calculating the integrated electron energy flux as is shown in figure 1-19 a) and b). This plot highlights the much greater intensity of the auroral arc at the flight's apogee (480-620 secs FT). Two points to be made about these plots are; the dip of the flux in both detectors at ~560 secs FT is due to the fact that the peak flux of the electrons went above the highest energy step on the CESAs, and the "wavy" appearance of the CESA2 flux in the two most intense arcs is due to spin modulation of the data. Figure 1-19 c) shows the energy of the peak electron flux for CESA1. This graph is instrumental in understanding the energy of the precipitating electron and relating the electrons to other phenomena such as rocket charging and ion heating, as will be discussed in the following section.

**Thermal Ion Observations**

The thermal ions were sampled by two capped hemispherical analysers (CHA) which swept in energy to ~22 eV and 755 eV every 920 msecs. This fast sweep time and the planar acceptance of the CHA allowed for high temporal resolution of the phase space distribution function. Thus a systematic method of presenting the full phase space data for the entire flight was decided upon (see Appendix B). A preliminary examination of the data was performed through a series of summary plots. These plots were averages of six energy sweeps (~5.5 secs) of data projections in the nrb coordinate system with a sampling period of ten seconds. A more detailed account of this procedure and the other procedures for final reduction and output of the data is given in Appendix B. These plots immediately revealed that there was a fundamental difference between the ions observed in the early portion of the flight and the ions observed in the two auroral structures of intense high energy electron precipitation (480-620 and 700-760 secs FT). Figure 1-20 shows the flight time 251.716 when a cold rammed plasma is observed. The left plot in the n-r plane (perpendicular to B) shows the ion flux below and to the left of the origin. Because this plot is in the rocket frame of reference without the payload potential taken out (a detailed description of this procedure in given in Appendix B), the ion flux is expected to be offset
TOPAZ 2

Phase Space Distribution

Log (sec$^3$/m$^6$)

Start Time 251.72

Figure 1-20
from the origin along the positive r-axis. The presence of the ion flux off of the r-axis indicates that there is an ion drift velocity in the western (to the left in the plot) direction. The most logical explanation of this drift velocity is the existence of a perpendicular electric field which would induce a bulk drift of the plasma (See Appendix C). The right plot in the r-b plane shows that the ion flux is also offset from the positive b-axis (the magnetic field line). Because the ion flux at this time was just being rammed into the detector this shows that the rocket was indeed on the upleg and that the trajectory was not aligned with the magnetic field. Figure 1-21 shows a very different picture of the ion population at flight time 495.019. The n-r plane no longer has a single centralized plasma flux location but instead the plasma flux is seen at a fixed radius nearly completely around the plane. The r-b plane has also changed dramatically, ions are now being detected flowing down as well as perpendicular to the magnetic field line. Thus a fundamental difference was immediately seen between these two ion populations. Further investigation revealed that there were in fact four different ion populations observed during the flight. The first of these populations observed was a cold rammed plasma.

Cold Rammed Plasma. During portions of the flight when the rocket was not in an intense auroral arc, the ion single particle distribution function was observed to be a well behaved cold rammed plasma as seen in figure 1-22 (see Appendix B for details on calculating f(v) from particle observations). From plasma theory it is well known (see e.g. Nicholson 1983, or Morgan 1976) that the single particle distribution function f(v) for cold ambient ions should be described by the Maxwellian function

\[
f(v) = N\left(\frac{m}{2\pi kT}\right)^{3/2} e^{-\frac{1}{2}\left(\frac{m(v - v_0)^2}{kT}\right)},
\]

Eqn 1-29

where \(m\) is the particle mass, \(N\) is the particle density, and \(T\) is the particle temperature. The bulk flow velocity of the ions, \(v_0\) is defined by;

\[
v_0 = \frac{\mathbf{E} \times \mathbf{B}}{\mathbf{B}^2} - v_r
\]

Eqn 1-30
TOPAZ 2
Phase Space Distribution
Log (sec³/m⁶)
Start Time 495.02

Figure 1-21
TOPAZ 2
Phase Space Distribution
Log (sec$^3$/m$^6$)
Start Time 253.55
where $B$ is the magnetic field, $E$ is the perpendicular electric field, and $v_r$ is the rocket velocity. The total particle velocity $v$ is defined as:

$$v = -\sqrt{\frac{2(e - e_U)}{m}} \hat{e}_i,$$

Eqn 1-31

where $e$ is the selected energy step of the HEEPS, $U$ is the rocket potential, and the unit vector $\hat{e}_i$ is normal to the collection area of the detector (a HEEPS accumulation bin in this case). The parameters which define $f(v)$ that are known from the flight data are: $v_0$, from the radar track of the rocket and calculation of the drift velocity from the electric field data and a magnetic field model; $v$, from the HEEPS energy step and estimated potential (discussed in Appendix B); and $m$ from the mass analyzer. Thus to fit the data to this Maxwellian function, theoretically only $kT$ and $N$ are required to be varied.

The first step taken in trying to fit this data to a Maxwellian was to display the raw data in order to try and get a better understanding of it. The top panel of figure 1-23 shows an example of this raw data. Pictured in the top panel figure 1-23 is data from HEEPS Low (HL) for eight consecutive image accumulation (energy step) periods with the flight time marked in the upper left hand corner. Each set of data contains the HEEPS Total Counts (HTC), as a solid line across the data, and the HEEPS Image for the accumulation bins listed on the horizontal axis. This is a typical looking data set for those times that cold rammed plasma was detected. The ion response is over a fairly narrow energy band (.16 to 3.5 eV here) and is well defined in bin space (FWHM ~ 10 bins = 50°). Also marked on the first and last panel is the earlier discussed ultraviolet contamination. This contamination appears to reduce during the detection of the thermal plasma. However this reduction is actually just a compression of the data due to the deadtime of the electronics. Retrieving the event rates for this data from equations 1-15, 16 and 17 reveal that the contamination remains at a constant level. The last criteria for a thorough examination of the data was to require that the entire azimuthal plane is covered. Due to the syncing of the energy sweep and rocket spin period three consecutive energy sweeps (~2.8 secs) of data are needed for completeness.

The first level of finding a Maxwellian fit was to generate a Maxwellian function numerically and then map it back into generated counts in the HEEPS accumulation bins.
Figure 1-23
Maxwellian Total Counts (KHz)  
Maxwellian Image (KHz)

HEEPS Total Counts (KHz)  
HEEPS Image (KHz)

Maxwellian Fit

HEEPS Raw Counts

TOPAZ 2
The program written to accomplish this calculated the Maxwellian using vector units in the \( \text{nrb} \) coordinate system. The program had input variables for rocket potential \((U)\), plasma density \((n)\), ExB drift magnitude \((V)\) and direction \((\phi)\), particle temperature \((kT)\) and mass. While some of these parameters can be determined by means of instruments on the payload, the flexibility to vary them allowed for the exploration of various numerical fits. In the case of the cross drift, often the best fit did not exactly match the electric field data but was within measurement error of the two instruments. Due to the lack of high time resolution data from the mass analyzer, the composition of the mass has been taken to be \( \text{O}^+ \). If the actual mass was \( \text{H}^+ \) then the phase space plots would remain the same with the velocities reduced by a factor of four. The best fit data for the raw data displayed in the bottom panel of figure 1-23. The plasma parameters for this fit are listed in the figure 1-24 and are discussed in the next paragraph. While only data from one energy sweep is shown, these parameters were found to be the best fit for the three consecutive sweeps to ensure there was no azimuthal biasing.

Once this microscopic fit had been made, these parameters were fed into a program which simply calculated the single particle distribution function and displayed it in the same manner as the observed data was displayed to give a macroscopic fit. This fit was then compared to the actual phase space data and adjusted if needed to find the best fit. If the parameters were adjusted then the new parameters were then fed back into the bin fit to check for self consistency. The fit of the phase space data in figure 1-22 is shown in figure 1-24 for these three energy sweeps. The data is presented in the rocket frame of reference without the payload potential being taken out. The data extends further out in phase space then the fit does due to the fact that the HEEPS did have a low noise rate which was not programed into the numerical fit. The plasma parameters found at this time are listed in the upper right hand corner of the plot. The fit temperature \((kT = 0.15 \text{ eV})\) show that this is indeed a cold ambient plasma. The small cross drift \((V = 1.0 \text{ km/s}, \phi = 90^\circ)\) from the fit differs from the calculated ExB drift \((V = 1.5 \text{ km/s}, \phi = 80^\circ)\) and implies a fitted electric field which is smaller and directed more southward then the measured electric field (from Cornell's dual probes). However the fitted field is correct to within the measurement error of the HEEPS.
TOPAZ 2
Phase Space Distribution
$\log (\text{sec}^3/\text{m}^6)$
Start Time 253.55

$n = 1000 \text{cm}^{-3}$
$U = 1.1 \text{ V}$
$kT = 0.15 \text{ eV}$
$V = 1.0 \text{ km/s}$
$\phi = 90^\circ$

Figure 1-24
Superthermal Tails. As the flight progressed a population of ions which had energies above thermal energies was detected. This signal was first seen in the downlooking (90-150° p.a.) OCTO detector. Figure 1-25 shows an example of a superthermal tail observed by the OCTO. The detector's pitch angle and energy sweep are shown in the top and bottom panels. As can be seen in figure 1-25, the large geometry factor OCTO was also affected by the intense ultraviolet emissions from the aurora. However, it is quite clear that as the detector was spun through 90° pitch angle there was a large response at the lower energy channels. The superthermal events seen in the OCTO are bunched into three time periods (350-395, 455-620, 710-800 secs FT) during the flight. A summary of the superthermal events detected by the OCTO is given in figure 1-26 where the events have been characterized by the highest energy detected during the event. The most energetic ions were observed during the time in which the payload was in the most energetic auroral arc. With the knowledge of the superthermal events existing in the OCTO data, the HEEPS data was then searched for similar events.

The search of the HEEPS data during times in which the OCTO had recorded superthermal events revealed similar events in the HEEPS data. However the number of events seen in the HEEPS during the specific times the OCTO had seen superthermal events was lower. This can be attributed to the fact that both HEEPS had smaller geometry factors than the OCTO and thus were not sensitive enough to detect all of the events. The signal of a superthermal event in the HEEPS was very distinct from that seen when only cold rammed plasma was present. An example of the raw counts is shown in figure 1-27. The superthermal events is detected over sixteen energy steps (0.4 - 11.2 eV) and is very pronounced in bin space (~8 bins = 40°). As a first attempt, the Maxwellian fit was tried to see if this was just a population that had been bulk heated to a larger plasma temperature. All of these attempts failed and showed quite clearly that this was not a uniformly heated Maxwellian plasma.

Klumpar et. al. [1984] have shown that an ion conic that they measured had a bi-Maxwellian distribution when it was mapped to its source region. Furthermore, the plasma had a perpendicular temperature approximately six fold higher then its parallel temperature. Thus, assuming that the superthermal events observed on flight 35.017 was similar, this data should be able to be fitted with the bi-Maxwellian function:
TOPAZ 2

Sweep (V) vs OCTO 2 (kHz) vs Angle (°)

Flight Time (0.05 sec/div)

Figure 1-25
Figure 1-26

TOPAZ 2
Superthermal Events

Energy (eV) vs. Flight Time (sec)
where $T_{\parallel}$ is the parallel plasma temperature, $T_{\perp}$ is the perpendicular plasma temperature, and the parallel and perpendicular velocities are defined as the vector sums of equation 1-31.

Like Klumpar et al. [1984], these observations of superthermal tails were not made at the source region but instead at a higher altitude. The distance to the most distant source region can be estimated from the measured pitch angle of the highest energetic particles of the superthermal event. Because no acceleration parallel to the magnetic field was detected (no elevation of the lowest energy particles in the parallel direction), the source region can be found from first determining the magnetic field strength at the mirroring point via equation 1-2 and then using a magnetic field tracing program to determine the altitude of this mirroring point. When this distance is known, a bi-Maxwellian fit can be generated at the source region and then adiabatically moved up the field line to the observation point. Thus the only parameters which changed in the programs to find the bi-Maxwellian fit are that now $T_{\parallel}$ and $T_{\perp}$ are inputs instead of $T$ and the distance to the source region must be input. The best fit to the raw data of figure 1-27 is shown in figure 1-28. Furthermore, the phase space data and fit are shown in figures 1-29 and 1-30 with the fit having required the same criteria as in the Maxwellian case.

There are a few observations which must be made about the phase space fit. Because the fit is such that it is being generated at the source region and then being mapped up to the observation region, the fit is only for the upward flowing ions. Secondly, because the fit is only dealing with the upward traveling superthermal tail it does not agree with the data on the first few steps where cold ambient stationary plasma is detected. With this in mind, the fit shows that the ions have a perpendicular temperature that is roughly ten fold greater than the parallel temperature.

In searching the HEEPS data for evidence of superthermal tails it was found that the majority of these events had durations of only one energy sweep. Therefore the bi-
TOPAZ 2
Phase Space Distribution
Log\( (s^3/m^6) \)

Start Time \ 423.13
TOPAZ 2
Bi-Maxwellian Fit
Log(s^3/m^6)

Start Time 423.13

\[ n = 100 \text{ cm}^{-3} \quad U = 1.0 \text{ V} \]
\[ kT_\perp = 1.30 \text{ eV} \quad V = 0.75 \text{ km/s} \]
\[ kT_\parallel = 0.15 \text{ eV} \quad \phi = 65^\circ \]
Maxwellian fit could not be attempted on a majority of these events due to the lack of azimuthal coverage. However, Reiff et. al.[1986] has shown that actual measured distributions can be numerically fit with the accelerated distribution:

\[ f(v) = N \left( \frac{m'}{2\pi kT} \right)^{3/2} e^{-\frac{E - E_{\text{peak}}}{E_0}}, \]  

\text{Eqn 1-33}

where \( E_{\text{peak}} \) is the peak energy, \( f(v) \) is the particle distribution function and \( E_0 \) is the best-fit characteristic energy. This numerical fit is called an acceleration distribution because when the logarithm of the particle distribution function is plotted versus the energy, the peak of the distribution is offset from the origin therefore indicating that it has been accelerated. Furthermore when the accelerated distribution is plotted in this manner, the inverse of the slope is simply the characteristic energy. Reiff et al. further emphasizes that the best-fit characteristic energy is usually several times larger than the best-fit thermal temperature \( kT \).

In the case of the data from the HEEPS instruments aboard flight 35.017 this can be explained by the fact that the data is not in the plasma frame of reference. The rocket velocity and estimated potential can be subtracted out to present the data in a stationary frame of reference but any small transverse electric field present at this time will cause the plasma to drift at velocities comparable to the ion thermal velocity. Thus, the distribution in the stationary frame of reference would be distorted and the inverse of the slope of this distribution would no longer be the temperature. However, if the direction in phase space over which the best-fit characteristic energy is calculated is limited to a small region then the found characteristic energy (\( E_0 \)) would pertain only to that direction. Thus it is possible to find the characteristic perpendicular and parallel energies by examining small portions of their phase space distribution function in the respective directions.

An example of a one-sweep superthermal tail is given in figure 1-31. Note that the data is displayed in a stationary frame of reference with the estimated rocket potential taken out (procedure explained in Appendix B). Thus the flux at the center of the graph is just the ambient thermal plasma that was present in the previous bi-Maxwellian fit case. The superthermal tail can be seen as a separate branch extending out in the perpendicular ("r vel") axis. The results of determining the distribution function along the gradient of steepest characteristic perpendicular energy is shown in figure 1-32. Also drawn on this
TOPAZ 2
Phase Space Distribution
Log (sec$^3$/m$^6$)
Start Time 465.52

Figure 1-31
TOPAZ 2
Characteristic \( \perp \) Energy
Start Time 465.52

\[ E_0 = 0.91 \text{ eV} \]
\[ E_0 = 11.48 \text{ eV} \]

Figure 1-32
graph is the best-fit characteristic energies for the thermal and superthermal ion populations. The thermal ions have a cold characteristic perpendicular energy of 0.91 eV while the superthermal tail is found to have a much hotter characteristic perpendicular energy of 11.48 eV.

While the HEEPS was found to be less sensitive at certain times to the superthermal events seen in the OCTO, it also was able to detect several low energy events the OCTO was not able to resolve. The two previous examples are two such cases. Figure 1-33 shows the summary of the characteristic perpendicular energy of all of the events detected by the HEEPS. As was the case in the OCTO data, the events with the largest characteristic perpendicular energy occurred during the time in which the payload was in the most energetic aurora.

**Down Flowing Ions.** The study of the HEEPS data during which times the payload was inside the intense auroral arcs led to the discovery of a population of cold thermal ions flowing down the magnetic field line. These ions were present from 455-620 secs FT and 675-760 secs FT. An example of the down flowing ions is shown in figure 1-34a. This is to be compared with the data shown in 1-34b which is from three energy sweeps later as the rocket has emerged from the auroral structure. Both plots are in a stationary frame of reference with the estimated potential subtracted out. The data at 619.43 secs FT has ions flowing down the magnetic field (in the + b direction) with the peak flux at approximately 3 km/s. Also present at this time are transversely accelerated ions (described in next section) with perpendicular velocities out to 8 km/s. The ions at 622.19 secs FT have their flux peak at approximately 1 km/s flowing up the magnetic field line (in the - b direction). In addition, at this time there is a superthermal tail present which shows the characteristic sign of being a separate population from the ambient ions. These two plots clearly shows the difference between times when down flowing ions were observed and those when ambient ions were observed.

To further show that the cold down flowing ions are a separate population the HEEPS raw data from ~496 secs FT is shown in figure 1-35. Pictured in figure 1-35 is data from HEEPS Low (HL) for six consecutive image accumulation (energy step) periods with the flight time marked in the upper left hand corner. Each set of data contains the HEEPS Total
Figure 1-34

TOPAZ 2
Phase Space Distribution
Log (sec³/m⁶)

Start Time 619.43

Start Time 622.19
Counts (HTC), as a solid line across the data, the pitch angle look direction (solid "sine wave"), and the HEEPS Image for the accumulation bins listed on the horizontal axis. It is evident from examining the data that two ion flux peaks are seen in the panels at 496.60, 496.63, and 496.66 secs FT. Examination of the pitch angle for the two peaks reveals that the peak centered around bin number 32 has a pitch angle of \(\sim 90^\circ\) while the peak centered around bin number 56 has a pitch angle of \(\sim 0^\circ\). Two other points of interest from this plot. The distinction between the two peaks is clearest at 496.66 because the HEEPS Total Counts has fallen to a rate at which there is no appreciable smearing of the image by the electronics. Secondly, the peak at \(\sim 90^\circ\) is seen to continue on in energy past the down flowing ions. This is expected because these are transversely accelerated ions (and will be discussed in the next section). The contamination from the ultraviolet emissions is also seen in the first and last two panels as that population between bins zero and sixteen.

Because this population seemed to be well behaved, a numerical fit to the data was attempted using the streaming Maxwellian:

\[
f(v) = N \frac{(m/2\pi k T)^{3/2}}{\pi^{1/2}} e^{-\frac{1}{2} \left( \frac{m(v - v_s)^2}{kT} \right)}, \tag{1-34}
\]

where the parameters are the same as in the Maxwellian fit given in equation 1-29 except the term \(v_s\) which is the streaming velocity and is directed along the magnetic field. However, as was the case of the majority of superthermal tails, the down flowing ions are changing over the time period required to satisfy the numerical fit criteria. The process of numerically fitting the down flowing ions is further complicated by the presence of either a small ambient population or transversely heated ions (discussed in the next section). Therefore because the downflowing ions could be numerically fit, they were characterized by the streaming velocity of the peak flux for each observed distribution function. This summary is given in figure 1-36. The streaming velocity is seen to vary up to 5 km/s and has an average over the time periods of roughly 3 km/s.
Transversely Accelerated Ions. As was shown in figure 1-21, the thermal ion population changes quite dramatically as the payload entered the two most energetic arcs. Figure 1-37 shows the phase space distribution function for an energy sweep while inside the most intense arc. A dramatic acceleration of the thermal ions in the transverse direction can readily be seen. Like the earlier reported superthermal tails, it was found that the individual transverse accelerated ion events varied on a time scale at least as small as one energy sweep (0.9218 secs). Thus once again the criteria for fitting these events to a bi-Maxwellian could not be fulfilled. Instead the distribution function was averaged over a finite pitch angle range in the perpendicular direction for each energy sweep and the characteristic perpendicular energy was found from this data. Figure 1-38 shows an example of this process. Note, that unlike the data in which both a superthermal tail and ambient ion population is seen (figure 1-32), at this time the entire ion population has been heated in the perpendicular direction to a characteristic energy of 6.9 eV (compared to the previous ambient characteristic perpendicular energy of 0.91 eV). A summary of the characteristic perpendicular energy is given in Figure 1-39. Outside the two intense arcs the characteristic perpendicular energy is averaged over six sweeps. In the cases of coexisting superthermal tail, the value given is that of the thermal core ions. Inside the intense arcs the characteristic perpendicular energy is for every energy sweep. Also plotted on Figure 1-39 for reference is the peak energy of the precipitating electrons.

Further inspection of the OCTO events shown in figure 1-26 revealed the coincidence of a large number of these events with the transversely accelerated ions. Because the OCTO swept to higher energies and had a larger geometry factor than the HEEPS instrument, this data is ideally suited to determining if the high energy tail portion of these ions is elevated. Figure 1-40 shows the OCTO data for four times when transversely accelerated ions were seen in both the HEEPS and the OCTO. The plots are the logarithm of the distribution function (vertical axis) versus the energy of detection (horizontal axis). The data presented is selected from a limited pitch angle range in the perpendicular direction so that the inverse of the slope of the best fit line is simply the perpendicular temperature ($kT_\perp$). The high energy tails are seen to vary between $kT_\perp = 110$ to 205 eV and are distinctly elevated from the thermal portion of the distribution. A fit was not attempted in the thermal range because of the lack of coverage in energy steps at those values. It should
TOPAZ 2
Phase Space Distribution
Log (sec$^3$/m$^6$)
Start Time 549.39

Figure 1-37
TOPAZ 2
Characteristic \perp Energy

Start Time 549.39

\begin{figure}
\centering
\includegraphics[width=\textwidth]{topaz2_characteristic_energy}
\caption{\textit{TOPAZ 2 Characteristic \perp Energy}}
\end{figure}

Figure 1-38
Figure 1-39

Peak Electron Energy

Characteristic Perpendicular Energy
also be noted that the data used to determine the high energy tail was over an order of magnitude higher than the one count level thus giving confidence to the calculation.

**Other Ion Observations.** Other on-board observations of thermal ions were made by the SuperThermal Ion Composition Spectrometer (STICS) provided by Marshall Space Flight Center. After the completion of the flight it was found by the team at MSFC that the STICS instrument had a geometry factor which did not allow for sampling at the pre-flight intended rate. Instead the data from the STICS must be averaged over a rather large time period (~20 secs). Thus the STICS data is unable to resolve any of the individual events (i.e. superthermal tail or transverse accelerated ions) seen in the HEEPS but it can give a good summary of data throughout the flight.

STICS is able to differentiate between the mass species H\(^+\), He\(^+\), O\(^+\), and NO\(^+\). The summary plots of these mass channels showed that: O\(^+\) was the most abundant species during the flight; H\(^+\) was detected in smaller amounts than O\(^+\) throughout the flight; He\(^+\) was hardly detected during the flight; and NO\(^+\) was found only on the down leg as the rocket passed through the f region.

The HEEPS data has shown that during the up and down legs of the flight the plasma observed is a well behaved cold rammed plasma which can be fit with a Maxwellian distribution function. During these times the STICS data can be averaged over the required time periods to produce phase space distribution plots. Furthermore Dr. Tom Moore has developed a computer routine to fit the to the Maxwellian distribution function of equation 1-29. Figure 1-41 shows the data (individual marks) and numerical fits (solid lines) for the H\(^+\) and O\(^+\) channels averaged over the down leg of the flight. The dashed lines in the plots are the one count level. Any data below this line is considered background noise. Both distribution function fits show that ions are indeed simple cold rammed particles with the plasma temperatures being well in the thermal range. The STICS data was also averaged over the time periods in which the payload was in the intense arcs. While the thermal core part of this data is suspect at the very least, the STICS instrument does detect a superthermal tail in H\(^+\) channel. The fit of this superthermal tail gave kT=15 eV in the direction of steepest gradient in distribution function. This compares well to the most energetic events observed at the same time by the HEEPS. While the composition of the
Figure 1-40
TOPAZ 2
STICS Data
Start Time 954.00

Figure 1-41
HEEPS data was assumed to be O⁺, the characteristic perpendicular energy of the superthermal tails would be the same for a H⁺ population. This is because the characteristic perpendicular energy is calculated from the slope of the logarithm of the distribution function versus the energy detected. A reduction of the distribution function by a factor of 16 (square of the ratio the masses) will not affect the slope and therefore leave the characteristic perpendicular energy unchanged. Thus even though the STICS data is limited it can be used in a supporting role for better determining the plasma response during the flight of 35.017.

Electric Field and Wave Measurements. The electric field and wave measurements were provided by Cornell University. Figure 1-42 shows a summary of the electric field and waves observed during the flight. 1-42a and b is the magnitude and direction (in geomagnetic coordinates) of the DC electric field. As the payload entered both intense auroral arcs the electric field ramped to values of 400 mV/M and fluctuated by as much as 300 mV/M. These high values of the electric field should cause a significant ExB drift (5-10 km/s) perpendicular to the magnetic field in the ion data. Instead the data lacks any such drift and forces the assumption from the particle point of view that the electric field measurement during this time is not accurate (a through explanation of this conclusion is given in Appendix C). However, it should be noted that this is only for times in the two most intense arcs, the Maxwellian fits performed for the up leg and down leg found values and direction which agreed within the measurement errors of the instruments.

Figure 1-42c gives a summary of the wave emissions observed during the flight. It is immediate obvious that there are three times of wave activity. It is also fairly obvious that these times correspond to the same times at which the rocket was within an auroral arc. Figure 1-42d shows the integrated electric field amplitude over the range 30-50 hertz. Kintner et al. [1989] has identified the emission at the times 475-625 and 660-800 secs FT as being electrostatic oxygen cyclotron waves. The peak amplitude of the integrated electric field for these times are 5 mV/M for the group at apogee and 1 mV/M for the last group. In addition to these waves, hydrogen Bernstein mode waves were also identified throughout the entire flight.
Discussion

The observations made aboard NASA flight 35.017 have provided new knowledge of the physical processes behind the transverse heating of ions. The implementation of the capped hemispherical electrostatic charged particle analyzer has allowed the sampling of two-dimensional phase space ion distribution functions with temporal resolution of approximately one second. This high time resolution paints a much clearer picture of the energy and pitch angle evolution during transverse heating events than has previously been recorded. The question which must be answered is how do these observations compare to the previous reports of observations of transverse ion heating and in what way can they help better understand which of the proposed theoretical mechanisms are at work. However, it is first appropriate to give a quick review of the data observations.

Electrons. The majority of the time of flight 35.017 was spent in the presence of auroral electron precipitation. This precipitation can be broken down into the passage through three discrete auroral structures. The last two arcs were observed to have intense high energy (15-20 keV) precipitation. Intensification of the monoenergetic peak was observed in the field-aligned direction. Low energy field-aligned electrons were also detected throughout the upleg portion of the flight.

Cold Thermal Ions. During the early portion of the upleg and late in the downleg of the flight cold rammed thermal ions were observed. These ions have been numerically fit with a Maxwellian single particle distribution function. During the downleg portion of the flight an anomalous thermal ion distribution was discovered. A thorough examination of this population determined that it was a likely candidate for having been produced due to the effects of the rocket's plasma wake. The discussion of this population has been limited to Appendix D.

Superthermal Ion Tails. Ion conics have been observed above 700 km altitude during the flight. A limited number of these conics (those with adequate azimuthal coverage) have been numerically fit with a bi-Maxwellian single particle distribution function which had a ratio $kT_\perp/kT_\parallel = 10$. The majority of the superthermal tails observed were detected for the duration of only one energy sweep (.9218 secs). These high
temporal/spatial duration conics were analyzed by charting their characteristic perpendicular energy. This perpendicular characteristic energy was variable and was seen to reach as high as 17 eV. Because the superthermal tails were observed with an ambient population, it is believed that these ions were transversely heated at altitudes below the rocket observations. Ion conics/ high energy tails have also been seen in the data from the large geometry factor OCTO detector. These ion conics/ high energy tails are seen during the times in which the payload is in the auroral structures. During the times in the auroral structures with high energy (>15 keV) electron precipitation, the high energy tails are observed at times in which transverse ion heating is observed. This high energy tail is seen to have a temperature in the hundreds of eV.

Downflowing Ions. Cold downflowing ions are seen in the two arcs of highest energy electron precipitation. An attempt to fit these ion with a streaming Maxwellian function was made. However, due to the variability of the plasma parameters over the energy sweep periods, the accuracy of this fit was deemed too uncertain. Instead a characteristic streaming velocity was found from each phase space distribution plot. This velocity varied between 0 and 4 km/s and had an average value of roughly 3 km/s.

Transversely Heated Ions. Transversely heated ions were observed during times of high energy electron precipitation. These two times were while the rocket was going through apogee (910-927 km) and on the downleg (830-790 km). The characteristic perpendicular energy of these heated ions were found to vary greatly during these time periods and reaching as high as 7 eV. Because ions at this time were seen to be bulk heated, it is believed that these ion were observed in a transverse acceleration region.

Plasma Waves. Kintner et al. [1989] has identified the emissions during the times 475-625 and 660-800 secs FT (periods of high energy electron precipitation) as being electrostatic oxygen cyclotron waves. The peak amplitude of the integrated electric field for these times are 5 mV/M for the group at apogee and 1 mV/M for the last group. In addition to these waves, hydrogen Bernstein mode waves were also identified throughout the entire flight.

A summary of the data is given in figure 1-43. In the top panel the characteristic velocity of the downflowing ions is plotted. The second panel shows the characteristic perpendicular energy (boxes) for the superthermal tails. The last panel shows the characteristic perpendicular energy of the thermal ions (solid line) and the peak energy of
Figure 1-43
the precipitating electrons.

These observation made aboard NASA flight 35.017 are in good agreement with several of the previous reports of transverse energization of ions. The geomagnetic planetary 3-hour-range indices for the time encompassing the flight reveals a value of $K_p = 3$ [Coffey 1988]. Thus all of these events would be categorized as occurring during magnetically quiet times according to the criteria established by Gorney et al. [1981]. The majority of the conics observed during the flight had energies below 400 eV in agreement with Gorney et al. While these authors showed that transversely accelerated ions were primarily seen during quiet times at altitudes between 1500-2500 km, the source regions detected during 35.017 were at a slightly lower altitude but certainly at the topside of the auroral ionosphere. It should also be pointed out that the particle instrument on board S3-3 had poor pitch angle resolution below 1500 km. Thus the study by Gorney et al. did not have available a large quantity of data in that region [Dave Gorney private communicate].

Unfortunately the results of 35.017 will not shed any light on the question of mass dependent transverse ion acceleration below potential structures [Collin 1986]. Because the transverse heating was observed while in regions of auroral electron precipitation, these observations should show the mass preferential heating proposed by Collin [1986]. However the lack of time resolution in the STICS instrument limits the amount of mass analysis that can be done. The time scales available from the STICS instrument is on the order of 30 seconds. The fluctuations of the characteristic perpendicular energy observed by the HEEPS instrument in the transverse heating regions showed time scales on the order of one second. Thus any sort of meaningful mass analysis of the individual transverse heating events can not be performed. The next in the series of topside auroral zone (TOPAZ) sounding rocket flights will have a dedicated ion composition capped hemispherical analyzer which should provide the needed high time resolution mass separated distribution functions to answer this question.

Perhaps the most closely related observations to those seen on flight 35.017 is the report by Yau et al. [1983] of two separate rocket flights through active auroral arcs. Both rockets passed through intense electron precipitation and transverse ion heating regions. As was the case of flight 35.017, field-aligned electron precipitation was seen at the edges of the auroral arcs. No correlation was seen by Yau et al. between the field-aligned
electron precipitation and the transversely accelerated ions. This same conclusion was made for the observations made by flight 35.017.

Observations of both ion conics and transversely accelerated ions were made by Yau et al. [1983]. The source region of the high energy ion conics was found to be between the

Source Regions of Ion Conics

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<th>$\alpha_{\text{min}}$</th>
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</table>

Table 1-6

altitude range of 400-500 km for one of the two rocket flights. A similar calculation was made to estimate the source region of the ion conics observed during flight 35.017. If the assumption is made that the particles in a superthermal tail have only been transversely accelerated in a finite region and then allowed adiabatically convect up to the observation point, then the magnetic field strength at the source region can be found using equation 1-2. The altitude of the source region was then found via a magnetic field line tracing program which used the International Geomagnetic Reference Field (IGRF) 1980 set of coefficients. The size of the source region is obtained by assuming that the upper pitch angle boundary particles came from the topside of the source region while the lower pitch angle boundary particles came from the bottomside of the source region. Table 1-5 list the time of observation, maximum and minimum pitch angles, altitude of observation, the maximum and minimum source altitudes, and the characteristic perpendicular energy of a few ion conics. These ion conics were chosen because they had the discrete angular resolution
such that the upper and lower pitch angle boundaries could be easily defined. The superthermal tails observed by flight 35.017 were found to have source regions which had overall heights of 200-300 km with the lowest source region being mapped down to 568.7 km. In the majority of observations, the topside of the ion conic source region was found to be just tens of kilometers below the rocket. Yau et al. have also shown that the characteristic energy of the observed ion conics increased with increasing source altitude. This is not born out in a comparison of the characteristic perpendicular energy and source altitude in table 1-5. Instead there is a vast fluctuation in the characteristic perpendicular energy with increasing source altitude.

Yau et al. [1983] reported ion temperatures which were obtained by fitting a Maxwellian to the observed thermal particle distribution function. The authors argued that there was a lack of evidence of bulk heating in their data. However, Yau et al. went on to present examples of the phase space density in the perpendicular and parallel directions in which the distribution in the perpendicular direction is seen to be elevated while in the defined region of transverse acceleration. Because the Maxwellian fit of the data at this time yielded unreasonably high temperatures, Yau et al. did not consider this data in the evaluation of the bulk heating of the particles. Flight 35.017 also observed the presence of elevated phase space distribution functions in what has been defined as a transverse acceleration region. However, while Yau et al.'s rejection of the unreasonable temperatures in the transverse acceleration region was justified, the presence in both data sets of distributions heated thermal cores in the perpendicular direction points to a bulk heating process in the transverse direction. If this was a process in which a perpendicular high energy tail was solely produced, such as the proposed lower hybrid acceleration model [Chang and Coppi 1981], then the distribution should show a distinct difference between the thermal population and the high energy tail. However, this is not the case, as is seen in figure 1-38 where the entire observed populations has been bulk heated in the perpendicular direction.

Yau et al. [1983] observed large fractional density fluctuations in the plasma and were able to identify the presence of Doppler-shifted O\(^+\) ion cyclotron harmonics using spectral analysis. The wave data taken aboard the second flight as reported by Yau et al. did not have any large amplitude waves. In contrast, the wave data observed aboard flight 35.017 did have large amplitude waves which have been identified as Bernstein mode waves and
electrostatic oxygen cyclotron waves [Kintner et al. 1989]. The correlation of the observations of the electrostatic oxygen cyclotron waves and the presence of a transverse ion acceleration region in the data from flight 35.017 does agree quite well with the results of Yau et al.

The three models for the production and transport of elevated ion conics [Klumpar et al. 1984, Horwitz 1986, Temerin 1986] are mainly applicable to observations made at much higher altitudes than those made by flight 35.017. In two of the theories [Horwitz 1986, Temerin 1986] the ions are required to travel large distances either perpendicular or parallel to the magnetic field. However, it is interesting to compare the observations and resulting transformation of data from Klumpar et al. [1984] to similar calculations made with lower altitude 35.017 data. Klumpar et al. observed elevated ion conics at an altitude of ~22,000 km. The authors were able to successfully map these distributions back through a parallel potential drop and then adiabatically back to the ions' source region at ~18,200 km. Inspection of the phase space density functions at the source region revealed that the distributions had distinct perpendicular and parallel temperatures. The temperatures derived were 1.17 keV for the perpendicular direction and 0.26 for the parallel direction thus giving a ratio of 4.50 for perpendicular to parallel temperatures. The good agreement of the fitted temperatures to the data inferred that the distribution was a bi-Maxwellian.

Because these measurements were made at a much higher altitude in the magnetosphere, one would expect the plasma temperatures to be higher than in the ionosphere. Yet by the same token, one would also expect that if the mechanism for the production of ion conics is similar at both altitudes then a comparison of the ratios of the temperatures should show comparable results. Figure 1-29 shows an example of an ion conic observed during flight 35.017. This ion conic was observed at 864 km altitude and had an estimated source region of 568 km altitude. The numerical fit of the data to a bi-Maxwellian at the source region that has been adiabatically convected up to the observation point yielded a perpendicular temperature of 1.30 eV and a parallel temperature of 0.15 eV (figure 1-30). This yields a ratio of 8.67 for the perpendicular to parallel temperature which is higher but still very comparable to the ratio of 4.50 found by Klumpar et al. It should also be pointed out that along with having comparable temperature ratio, it is especially significant that both data sets revealed that the ion conics at source region can be
described by a bi-Maxwellian distribution. This ability to map the conic to a source region below the observation point and that the ions were not heated for the entire distance to the payload leads to the hypothesis that the transverse energization of the ions occurs over a finite altitude region.

The data from flight 35.017 should also help shed some light on which theory of transverse ion acceleration (electromagnetic ion cyclotron resonance, lower hybrid acceleration, electrostatic ion cyclotron turbulence, or narrow potential jumps) was the most probable candidate for producing the observed transversely accelerated ions. The theory put forth by Chang et al. [1986] showed how ions are transversely accelerated by electromagnetic ion cyclotron resonance with broad band left-hand polarized waves. In order to accelerate the oxygen ions to levels comparable to those seen by the DE-1 spacecraft the theory requires only 12% of the low frequency field spectral density to be left-hand polarized electromagnetic waves. However the observations made during flight 35.017 do not support the assumption that the ions were transversely accelerated by electromagnetic cyclotron resonance. It has been reported by Kintner et al. [1989] that the detected emission spectrum frequently exhibited a narrow peak above the oxygen cyclotron frequency during the times when the payload was in the first region of transverse heating. At other times while still in this acceleration region the spectrum had a broad peak centered on the oxygen cyclotron frequency or even peaks below the oxygen cyclotron frequency. The authors identify these emissions as electrostatic oxygen cyclotron waves (the waves being consistent with the expected Doppler shifting and broadening of electrostatic oxygen cyclotron waves) and show two arguments that these waves do not exhibit a electromagnetic nature. The first point presents the fact that the phase velocity of an electromagnetic emission should be much greater than the relative motion between the payload and the ambient plasma (~5 km/s) and therefore no spectral features should be seen above the oxygen cyclotron frequency. Secondly, Kintner et al. present a lengthy argument in which they show that the emission is linearly polarized, as is expected for an electrostatic emission. Thus due to the nature of the previous two arguments, it is not likely that the transverse acceleration of ions during flight 35.017 could have been produced by electromagnetic ion cyclotron resonance.

A second proposed mechanism for the production of ion conics is the transport of ions through oblique double layers [Borovsky 1984]. Borovsky has shown by use of a
# Double Layer Correlation

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<tr>
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Table 1-7
computer simulation that the passage of low energy O\(^+\) through an observed auroral double layer (reported by Mozer et al. [1977]) resulted in a conical distribution. Thus it follows that if this mechanism is responsible for the observed transverse ion acceleration then a correlation between the presence of double layers and ion conics should be observed. Narrow potential jumps were seen in the electric field data [Kintner private communication] during the flight of 35.017. Table 1-6 list the times of several of these narrow potential jumps and which types of ion populations were observed during that same period (STT-superthermal tails, TAI-transversely accelerated ions, DFI-downflowing ions). The reported narrow potential jumps are taken from times when the payload was in one of the two acceleration regions (480-629 or 710-760 secs FT). It is immediately clear that the potential jumps are not correlated with the superthermal tail population. The narrow potential jumps are also seen in conjunction with transversely accelerated ions fifty percent of the report times. Thus once again the observational evidence points to the conclusion that the observed transverse ion heating detected by flight 35.017 was not due to propagation of ions through oblique double layers. It should be noted that the narrow potential jumps do correlate well with the downflowing ions. However the downflowing ions are also seen at times before and after the acceleration region when the narrow potential jumps are not present. Thus any sort of correlation between the two must be a tentative one.

It has also been shown that ions can be transversely heated along auroral field lines by electrostatic ion cyclotron waves [Okuda and Ashour-Abdalla 1983]. Through the use of linear theory, Okuda and Ashour-Abdalla have demonstrated how the ion cyclotron waves are driven unstable by a upgoing cold ionospheric electrons. Figure 1-44, taken from Okuda and Ashour-Abdalla [1983], shows results of the marginal stability analysis to calculate the hydrogen temperature anisotropy for a given electron drift. The axis of the figure are the ratio of the Hydrogen perpendicular temperature to the Hydrogen parallel temperature \((T_{H\perp}/T_{H\parallel})\) on the vertical and the ratio of the electron drift velocity to the electron thermal velocity \((V_{de}/V_{le})\) on the horizontal. The different contours represent the results for different values of the ratio of the electron parallel temperature to the Hydrogen parallel temperature \((T_{e\parallel}/T_{H\parallel})\). Typically \(T_{e\parallel}/T_{i\parallel} \approx 1\) in the ionosphere and ion temperature anisotrophies have been observed to be \(\approx 10\). Therefore according to figure 1-44 a reasonable assumption for this scenario is to have the electron drift speed comparable
Ion Temperature Anisotropy

![Graph showing ion temperature anisotropy with axes labeled $T_{ML}/T_{HH}$ vs. $V_{de}/V_{te}$ and contour lines for $T_{eII}/T_{HH} = 0.5$.](image)

Figure 1-44
to the electron thermal speed \( (V_{\text{de}} = V_{\text{te}}) \). Further it was found in simulations by the authors that when the electron drift speed was comparable to the electron thermal speed, large amplitude coherent ion cyclotron waves exists over a finite region (~100 km) along an auroral field line. These waves have been shown in computer simulation by Okuda and Ashour-Abdalla to bulk heat the ions by as much as a factor of ten from original ionospheric temperatures and also produce a high-energy tail that is heated to a factor of one hundred times the initial thermal energy.

Okuda and Ashour-Abdalla [1983] have also shown that the altitudinal range over which ion cyclotron turbulence can transversely accelerate ions is limited due to parallel ion heat loss and the formation of a plateau in the electron distribution. The interval over which the ion are transversely heated is defined as:

\[
l_i = \rho_i \left( \frac{m_i}{m_e} \right)^{1/2} \left( a^2 \frac{D_B}{D_\perp} \right),
\]

Eqn 1-35

where \( \rho_i \) is the ion cyclotron radius, \( a \) is the transverse size of the electron beam, \( D_B \) is the Bohm diffusion coefficient, and \( D_\perp \) is the cross-field particle diffusion coefficient. Okuda and Ashour-Abdalla assume for \( V_{\text{de}} = V_{\text{te}} \) that the transverse heating region is ten times larger than the ion gyroradius and that \( D_\perp \) is comparable to \( D_B \). This reduces equation 1-35 to:

\[
l_i = 100 \rho_i \left( \frac{m_i}{m_e} \right)^{1/2}.
\]

Eqn 1-36

Further Okuda and Ashour-Abdalla predict that the instability runs in a steady state which propagates to higher altitudes within the acceleration region with a propagation speed approximated by:

\[
v_p \approx 0.01 \ V_{\text{de}},
\]

Eqn 1-37

where \( V_{\text{de}} \) is the electron drift speed.
In the case of flight 35.017, if it is assumed that the cold rammed plasma which was detected early in the flight is comparable to the ambient plasma where the instability occurs, then estimates of the heating region can be made using Okuda and Ashour-Abdalla's model. If the ambient ion temperature is taken to be $\sim 0.15$ eV, then the gyroradius of O at 600 km altitude is $\approx 13.5$ m. The scale length of the acceleration region would then be $\approx 230$ km. If it is further assumed that the electron temperature is $\sim 0.5$ eV and that $V_{de}=V_{te}$, then the propagation speed would be $\approx 2.8$ km/s and the instability would be able to run in steady state for a period of $\approx 82$ s. The calculated altitudinal range for the acceleration region agrees very well with those ranges found in table 1-5 from the observations of superthermal tails. The heating region which the payload passed through at apogee lasted for a 140 s period which is also comparable to the calculation. Because this heating region was detected at the rocket's apogee the altitude varied by only $\sim 20$ km. The heating region detected on the downleg lasted for approximately 45 s over an altitude range of $\sim 60$ km. The heating regions proposed by Okuda and Ashour-Abdalla [1983] are along a magnetic field line and have the transverse scale length of tens of ion gyroradius. Because flight 35.017 was not field-aligned the measurement of the altitude range and time in the transverse ion acceleration region can not be considered as that for a single heating region as defined by Okuda and Ashour-Abdalla. However the comparison is useful to show that the predictions by Okuda and Ashour-Abdalla are not unreasonable.

Ion beams and electron drift have been shown to be two possible sources for current-driven ion cyclotron turbulence [Kindel and Kennel 1971]. The model for an unperturbed F region ionosphere has a critical current density of $j_c \approx 100 \, \mu$amp/m$^2$ for $n_e \approx 10^5$ cm$^{-3}$. The data from flight 35.017 did not reveal any upward flowing ion beams as candidates for setting up this current. The down flowing cold ions do constitute an ion beam which carries current. Examination of the data summary given in figure 1-43 shows a definite correlation between transversely accelerated ions and down flowing ions. A calculation of the amount of current carried by these down flowing cold ions revealed that the current carried by this population was significantly below, $j \approx 0.1 \, \mu$amp/m$^2$, what is needed to set up a current instability. It should also be noted that the down flowing ions do not correlate well with the superthermal tails present in figure 1-43. The superthermal tails reported by the HEEPS instrument are assumed to be ions that have been transversely heated at some
altitude below and have adiabatically convected to the observation point. The superthermal tail presented in figure 1-32 was found to have a transient travel time of \( \sim 85 \) seconds from the top to its calculated source region (table 1-6). Assuming the up flowing superthermal tails and down flowing ions are located on similar field lines associated with an acceleration region, the lack of their correlation puts forth further evidence that the acceleration region has a finite altitudinal range and time duration (i.e. the down flowing ions are not continuously streaming down the field line into a steady-state acceleration region).

No scientific magnetometer was on board flight 35.017 to infer electron drift. However, the current associated with the field-aligned keV electrons has been computed and is shown in figure 1-45. It is seen that for the times in which the payload was in an auroral structure, the current was \( \sim 5 \) \( \mu \)amp/m\(^2\) and may have reached as high as \( \sim 10 \) \( \mu \)amp/m\(^2\) for those times in which the energy peak of the precipitating electrons when beyond the CESA energy sweep (\( \sim 550 \) secs FT). While this is below the above stated threshold, the model shows that this critical threshold current density is strongly dependent on the ambient electron density. Thus if the electron density in the high energy electron auroral structures observed by flight 35.017 were depleted (as Yau et al. [1983] have shown times for similar conditions) then this current would exceed the critical density value.

In conclusion, flight 35.017 has provided a platform at the topside of the ionosphere from which a study of anisotropic ion heating could be performed. The identification of four types of populations of ions (cold rammed plasma, superthermal tails, down flowing ions, and transversely heated ions) has been made. The superthermal tails (or alternatively ion conics) are believed to be ions which have been transversely heated at some lower altitude and adiabatically convected up to the observation point. The superthermal tails have been numerically fit with a bi-Maxwellian single particle distribution function which had a ratio \( kT_\perp/kT_\parallel \approx 10 \). The superthermal tails have also been mapped back to their source region revealing a finite heating region with overall heights of 200-300 km. The bottomside of these source regions was seen to vary from \( \sim 570 \) km to \( \sim 710 \) km.

Flight 35.017 also passed through two regions of transverse ion acceleration. These ions were seen to be bulk heated in the transverse direction and revealed a temperature anisotropy ranging up to a factor of 7. These regions correlated exactly with the times in which the payload was in auroral structures with high energy (>15 keV) electron
TOPAZ 2
Measured Field-Aligned Current

Figure 1-45
precipitation. The transversely accelerated ions are also seen to correlate with down flowing cold ions observed during the flight. The down flowing cold ions are seen at times before the onset of transverse ion heating but a calculation of the current carried by these cold ions was found to be far less than is needed to cause an instability in the plasma. Electrostatic oxygen cyclotron waves have been reported by Kintner et al [1989] during times in flight 35.017 which correlate with the two heating regions. High energy tails have also been detected in the heating regions. These high energy tails have perpendicular temperatures in the range of hundreds of eV.

The consistencies between the observed features in the ion data and the predictions of the ion cyclotron acceleration model further point to it being the most likely mechanism for the reported transverse heating. In a simulation of the constant-flux model, Okuda and Ashour-Abdalla [1983] showed a bulk heating of ions in the perpendicular direction of $kT_\perp/kT_\parallel \approx 10$ and a high energy tail with temperatures $\approx 100 kT_\parallel$ for a system having $V_{do}/V_{te} = 1.4$. In addition, this model also predicts altitudinal size and temporal durations of heating regions which were found to within reason of those found for flight 35.017. Thus the predictions of the ion cyclotron acceleration model are found to be in good agreement with the observations of flight 35.017.

The results from NASA flight 35.017 have been able to answer three of the four main questions sought from this experiment. The thermal ions have been seen to have greatly varying characteristic perpendicular energies in the heating regions suggesting fine temporal/spacial structures. Both electrostatic oxygen cyclotron waves and hydrogen Bernstein mode waves were detected during the flight with the EOC waves having a positive correlation with times of transverse ion heating. Finally, the characteristics of the transversely heated ion distributions and heating regions were shown to be consistent with an ion cyclotron acceleration model. However, a better understanding of the cause of the instability in the electrostatic oxygen wave and free energy source which drives it must be studied in future missions.
SECTION 2: EXPERIMENTAL PREPARATION
OF NASA FLIGHT 35.020

Introduction

The observations described by an experimenter and the subsequent theories which are
generated from this data can only be valid if one makes extensive pre-flight preparations of
a detector system. These preparations can take the form of many different tasks, from
calibrating the instrument to preventing a defect found to occur in a previous experiment.
In order to make the payload for NASA flight 35.020 the best platform from which the
desired scientific measurements could be made, three assignments were performed. The
first of these was the upgrading of the existing calibration facilities.

The most ideal setting for the calibration of a rocket payload would be a station in
which the entire experimental package could be housed and a outer-space like atmosphere
existed. However, such a calibration facility is not financially feasible. Instead a more
practical approach an investigator can try is to simulate the experimental environment for a
single detector system. When the field of view of the particle detector is narrow, all that is
required is a particle point source and a rotational feedthrough. With the advent of capped
hemispherical analysers (CHAs), which have an azimuthal view angle of up to 320°, this
simple setup becomes quite inadequate. Thus for the calibrate of the particle package on
flight 35.020, the MRL lab built a calibration facility with a broad beam electron and ion
source as well as a five axis positioning table on which the detector systems could be
mounted.

The second major task in preparation of flight 35.020 was the prevention of ultraviolet
contamination. As was discussed in Section I, the CHA's microchannel plate will produce
false counts when struck by an ultraviolet photon. During very active aurora intense UV
spectra has been measured [Ishimoto et al. 1989]. Traditionally electrostatic analysers have
some sort of absorption coating on their parallel analyzer plates to help eliminate this
problem. One of the most common coatings used in satellites is black gold. However, this
is an expensive process which is performed by only a handful companies in the United States. It was found, to the contrary, that the process of coating detectors with a metal black is relatively simple and can be done inexpensively in the lab. A study was performed to find what work had been done on this field, what metals could be used, and formalize the standard procedures for coating the detectors with black metals.

The third and most important pre-flight preparation for flight 35.020 was the actual calibration of the CHAs. Flight 35.020 is equipped with seven fixed energy electron CHAs, two sweeping electron CHAs and two sweeping ion CHAs. Because the seven fixed energy CHAs are planned to form a high time resolution picture of precipitating electrons, it is essential that the individual characteristics of each instrument is thoroughly known. Using the new broad beam source, three inherent traits of the detector were examined. Those traits were; the energy bandwidth of acceptance, the response of acceptance to the change in polar angle, and the azimuthal look angle of each bin. Understanding of the individual characteristics of the detectors allows for the generalization of the data so that results from the various CHAs can be compared directly.
Several components are needed to have a complete calibration facility. The first and foremost element is the vacuum system. When using an electrostatic analyzer (ESA), a large voltage is applied across the conducting plates in order to select the desired particle energy. The compact ESAs which are flown on rockets require that the space between these plates be small for bulk constraints and to minimize deformity in the applied electric field. Thus, if the ESA's high voltage sweep is turned on at atmospheric pressure, an arc will occur and damage the electronics and or analyzer plates. In order to avoid this, the ESAs are operated in a vacuum chamber at low pressures. In 1986 the MRL laboratory received a grant from the Air Force Office of Science Research to upgrade its vacuum chamber and calibration system. After a thorough study of available vacuum systems, it was decided to purchase the necessary equipment and assemble them into the lab's own unique vacuum station.

Vacuum System

In a laboratory where the fine tuning of particle detectors is an ongoing process, the ability to rapidly pump down to high vacuum from atmosphere is a very desirable quality. This rate depends on two of the system's main features, the cryopump's gate valve size and the size of the chamber which has an upper limit determined by the cryopump total capacity. Several factors were considered in the design of MRL's vacuum chamber. Planning of the electron gun, discussed in following paragraphs, for this calibration facility was started simultaneously with the design of the chamber. The electron gun design varied from previous photoelectric electron guns in that it is housed totally inside the chamber. There would also be a need for space for a positioning table to be designed at a later date. With these constraints in mind, a custom order stainless-steel cylindrical chamber was made for MRL by Sharon Vacuum of Brockton MA. The chamber is 30" in diameter and is 36" long with convex doors at each end. In order to have adequate external support, the chamber has: twelve 2 3/4" flanges for high voltage (MHV), low voltage, and signal (BNC) instrumental feedthroughs; two 8" flanges for possible auxiliary chambers; four view ports;
and a 6" flange on each door. The standard two pump system is used to evacuate the chamber, one pump for roughing to the millitorr range and the second for reaching high vacuum. The roughing pump and the high vacuum pump, a liquid helium cryopump, are both Varian models. The roughing pump runs at a rate of 27 cubic feet per minute and reaches the cross over juncture at roughly a quarter of an hour after turn on. The cryopump is then able to lower the pressure in a clean chamber to the 10^{-6} Torr range in an additional fifteen minutes. This enable an experiment to be brought to atmospheric pressure, checked and adjusted and then returned to being calibrated in under an hour. This is a great asset when compared to a whole day turn around time when the calibration facility was previously housed in a turbo vacuum pump chamber. A schematic of the system is shown in figure 2-1. An important feature that should also be noted is the presence of molecular filters in the form of two sieve traps. Located between the roughing pump and chamber as well as between the roughing pump and cryopump, the sieve traps keep oil from backstreaming to an area of high vacuum and thus preventing the system from being contaminated from this oil. It should be noted that the sieve traps are placed between two valves to insure that the traps are under vacuum before the chamber/cryopump valves can be opened.

**Photoelectric Electron Gun**

With the suitable environment and housing secured, the next part of a calibration facility is the particle beam. The goal in calibrating an instrument is the determination of the energy independent geometry factor \( G_0 \). Knowledge of \( G_0 \) allows the experimenter to express the counts detected by an instrument as a differential directional particle flux \( J \) (a full discussion of this procedure is given in Appendix B). Single directional ESAs needed only a narrow well defined energy peak of a thermionic emission or radioactive beta decay point source to be calibrated. The development of the wide angle azimuthal imaging capped hemispherical analysers demanded a different calibration system. The need to simulate the conditions detected in the ionosphere by the CHAs dictated the development of a broad beam particle gun. A similar broad beam particle gun had been developed for the calibration of ESAs at the Air Force Geophysical Laboratory at Hanscom AFB [Marshall et al. 1983, 1986]. Following the AFGL basic design, it was proposed to build a broad beam particle gun by illuminating a thinly plated quartz window with UV causing the emission of
photoelectrons. These electrons would then be accelerated by an applied voltage to form an electron beam at a desired energy level. With the freedom allowed by the size of the vacuum chamber, it was decided that the entire particle gun apparatus would be housed inside the chamber. This discussion was also made with the idea that the best way to evenly illuminate a large quartz window would be to have an equally large UV source. Thus the final composition of the photoelectric electron beam gun is shown in figure 2-2.

**Ultraviolet source.** The UV source chosen was an eight" square e-prom eraser lamp from Ultraviolet Products (UVP). The lamp is a seven millimeter diameter tube which has been shaped into several rows to form the square. The low pressure lamp radiates almost its entire intensity at the resonant UV emission line 2537 Å. The resonant radiation is the result of mercury's atomic transition from its lowest excited state to its ground state. A low vapor pressure will give the highest probability of transmitting this radiation to the outermost layer of the gas [Koller 1952]. The lamp is mounted on a reflector in order to make the source more uniform. The theory behind the reflector is the application of the law of reflection with the lamp's tubes mounted on ribs between grooves. The reflection of the light by the grooves fills in the spaces between the rows of the lamp. The grooves and ribs were machined from a rectangular aluminum plate which measured 13" x 9" x 0.75". The plate was also designed at first to serve as a heat sink to help diffuse the heat generated from the lamp being powered by a AC supply. However, it quickly was seen that the 60 Hertz cycling of the lamp due to the AC power supply was transmitted into the electron beam. The arc could be powered by a DC regulated power supply, but it was found this method could not produce a stable arc with the desired regularity. However, a spare lamp's arc stability was tested for varying temperature. It was found that the lamp's arc was very stable when it was heated beyond a certain temperature. Koller [1952] has shown for a low pressure mercury arc lamp that the relative UV output at 2537 Å reaches approximately 100% when the bulb wall is heated to between 100 and 110° F. With this in mind, a heating unit in the form of a molybdenum filament was epoxied into channels machined into the back of the reflector plate allowing the lamp to be uniformly heated. The power supply of the heating unit is operated externally which allows the lamp's temperature to be adjusted and maintained while the gun is in use. The separate DC regulated power
Photoelectric Gun

A: Reflector Plate
B: Reflector Hood
C: Diffuser Mount
D: Photocathode Mount
E: Acceleration Screen
F: Electron Gun Frame
G: Ultraviolet Lamp

- Aluminum
- Macor
- Stainless Steel
supply controlling the intensity of the lamp also is externally adjustable.

**UV Diffuser.** To make the incident beam further uniform, it is passed through a ground quartz window. The ground quartz diffuser is an 8.0-inch diameter 0.33-inch-thick made from Dynasil 4000. Middleton [1960] has shown the effectiveness of ground quartz in diffusing UV. The lamp, reflector and ground quartz window are within a aluminum hood to prevent the leakage of UV into the detectors via reflection off the walls of the vacuum chamber.

**Photocathode Window.** The photocathode window is an 8" diameter 0.325" thick fused silicon quartz piece with a 350-Å thick coating of chromium applied by Computer Optics Inc in Hudson, NH. The coating was applied to the inner part of the window such that the outer 0.2" of the window had no coating applied to it. Chromium was chosen as the photoelectric metal because of its durability in everyday use. This feature is cost effective because the original will in all likelihood suffice for the life of the electron gun. Unlike chromium, gold is not durable and this requires recoating of the photocathode window annually. Chromium also has a work function of 4.50 eV [CRC handbook], similar to gold, and therefore low enough to have its electrons ejected by 2537-Å light. The photocathode window is mounted in a 12" diameter frame with a 7.5" diameter opening. Electrical contact is made between the frame and photocathode window by a finger spring. The photocathode frame is isolated electrically from the chamber by being mounted on a 2" high piece of Macor, a machinable ceramic. To further protect the system from a high voltage arc, all of the corners of the photocathode frame have been rounded with radius of curvature of 0.25". The photocathode window and frame are shown in figure 2-3.

**Acceleration Screen.** Once ejected, the electrons are accelerated by a negative voltage applied to the photocathode window and frame. Immediately in front of the photocathode frame is an acceleration screen which is grounded. The acceleration screen is identical in size and shape as the photocathode frame with the exception that the inner 7.5" diameter is covered with a wire grid made up of 0.004" diameter stainless steel wire with a
Photocathode Frame and Window

Figure 2-3
spacing of 0.125" between each wire. The calculated open area of the grid is 93.6 % and has been coated with aerodag to reduce any reflection of ultraviolet light back onto the photocathode. The distance from the edges of the photocathode frame and the acceleration screen are large to prevent any distortion of the electron beam from edge effects of the acceleration field. The high voltage is supplied by an source external to the chamber which can be operated manually or by computer control.

**Positioning Table**

The second piece needed for a complete calibration facility is the housing for the detector in the vacuum chamber. After review of cost and designs of current commercial positioning tables, it was determined that it would again be in the best interest to manufacture the positioning table in house. Thus a five-axis table was built by the University's Space Science Center machine shop. Figure 2-4 shows the positioning table and its various range of motion. The table can move by as little as 0.001" or rotate by as little as 0.1°. The three rotation motions (yaw, pitch, and roll) can be best understood from a viewpoint of an airplane pilot. As a pilot flying a plane on a level trajectory the independent motions would cause:

1) yaw the nose of the plane would move to the right or left,
2) pitch the nose of the plane would move up or down,
3) roll the body of the plane would spin.

The motors for the table were furnished by Eastern Air Devices and have the added feature that they power down after reaching a desired position. This allows for selecting a single orientation for the table during long calibration runs without worry of burning out the motors or affecting the vacuum environment. As with the rest of the calibration facility, the positioning table can be operated both manually or by computer command.

**Computer Control**

The operation of the calibration facility has been greatly automated and simplified by the addition of a computerized operating system. A schematic of this system is shown in figure 2-5. The backbone of the system is a Dot personal computer. The Dot is a portable IBM PC compatible that was produced by Computer Devices Inc. A specific programing
Positioning Table

Axis
1: Yaw
2: Pitch
3: Roll
4: Horizontal
5: Vertical

figure 2-4a
P. T. Rotation Axis

- Pitch
- Roll
- Yaw

figure 2-4b
language was developed by Mark Widholm and Hank Dolben for the Dot's use in automating the calibration facility. This language was named Zip™. Zip™ runs under MS.dos and allows the users the freedom needed to customize a series of programs to calibrate the various different instruments that make up a rocket payload's particle detection package. Among the different functions which have been written in Zip™ to help are; sweeping of the applied voltage of the photocathode window a desired percentage from an initial value, single and multiple move commands for the positioning table, varying of the UV lamp intensity, and selection of the time accumulation interval. This last feature helps prevent the eight bit counter in the Dot from overflowing. However, in order for the software to be ran successfully on the Dot, it must have the necessary hardware connections.

The Dot's electronic connections to the calibration facility is located in two different locations. The first is the vacuum controller which oversees all of the tasks of the vacuum system. The Dot sends information on the different valves' position and pump status via a digital output line while it receives an analog input from the ion gauge controller via the vacuum controller. The ion gauge controller monitors the chamber's ion gauge and thermocouple as well as the thermocouple in the cyropump itself. A second analog input sends the temperature of the cyropump head calculated from a calibrated diode. The third and last analog input from the vacuum controller to the Dot is the reading from a thermistor attached to the cooler's water line. The second port for the Dot's commands is the Particle Energy Analyzer Calibration System (PEACS). PEACS contains the power supplies for the positioning table's motor controller, the lamp, its heater, and the applied potential. The Dot is connected to the motor controller's microprocessor via an RS232 serial port. The applied potential and ultraviolet lamp power supplies are hooked in parallel to the Dot via an analog output. These supplies can be controlled externally in order to assure the desired setting, or they can be swept singularly or dually by the Dot. The gun power supply has an upper limit of 40 kilovolts. The lamp heater, though mounted on the PEACS panel, is controlled completely external. The heater can be adjusted to the desired temperature and indicates if it is heating.
Computer Control Schematic

Vacuum Controller → Ion Gauge Controller → Dot Computer

30 Volt Power Supply → Lamp Power Supply → Gun Power Supply

Cryopump Head Diode → Cooler Waterline Diode → Vacuum System

Motor Controller → Ultraviolet Lamp → Applied Potential

Positioning Table → Lamp Heater

RS232 serial port → PEACS

digital output → analog input → analog input → analog output

figure 2-5
Calibration Detector

With the calibration facility completed, a well understood analyzer was needed to map the characteristics of the UV lamp and electron beam. Because of its uncomplicated attributes, a collimated channel electron multiplier (CEM) was used as the template for the design of the calibration detector (CD). It was required that the CD should be able to map both the lamp's and beam's intensities, have the capability to have both a fine angular (< 2°) and energy resolution, and finally that each of these modes should be easily enabled. The lay out for the CD is shown in figure 2-6. The CD consist of three collimating lenses, a removable photocathode lens, three acceleration screens, a spiraltron and its electronics.

The first priority addressed was the ability of the CD to map the characteristics of the UV lamp. It is well known that a CEM will count ultraviolet photons. However the efficiency of a CEM at 2537 Å is less than 10%, therefore at the lamp's normal operating intensities, the count rates were in the range of a few hundred hertz. Because the statistics at these rates are not acceptable unless large accumulation times are used, a method to increase the counts from the UV lamp had to be found. The obvious choice was to integrate a photodiode into the design of the CD. The photodiode portion of the CD would simply consist of a quartz window coated with a thin film metal (same as the principle behind the photoelectric electron gun) placed behind the CD's collimating plates. The photodiode could then adequately map the UV intensity because the photoelectric current is directly proportional to the intensity of the incident light provided the acceleration voltage is large enough to accelerate all emitted photoelectrons [Hughes and DeBridge, 1932]. It was also expected that the count rates of the photodiode should be approximately in the tens of kilohertz because it should be comparable to those found during the initial testing of the electron gun.

During the period when the electron gun's photocathode was being re-plated with chromium, a 1.25" diameter quartz window sample was plated with a thin film of copper (details of this operation are given in the next section) and then exposed to the UV lamp under vacuum. It was found during this electronics test, that the copper coated window did indeed work as a electron gun. The size of this quartz window sample showed it was feasible to use a copper coated photodiode in the CD. However, a few lessons about the photoelectric effect were learned in this process.
Calibration Detector

Collimation Lenses
Removable Photodiode Mount and Base
Acceleration Screens
Spiraltron and Mount

Figure 2-6
The CD's photodiode quartz window was first coated with a thin layer of copper. The photodiode was placed in the CD and exposed to the UV under vacuum. The CD registered a counting rate of ~30 Khz. This test was done on a Friday afternoon. The CD remained in the vacuum chamber under a pressure in the low hundreds of milliTorr over the weekend. Upon testing the CD on Monday, the count rate was seen to have dropped to below 5 Khz. Research into the subject turned up a discussion on this effect which was first dubbed photoelectric "fatigue" [Hughes and DeBridge, 1932]. During the beginning years of study of the photoelectric effect experimenters noted that as a metallic surfaced aged, the number of electrons emitted decreased. Detailed studies of this problem showed however that this was not an inherit trait of the metal due to the photoelectric effect, but instead it was the occlusion of gases by the metal's surface. Thus a metal like copper which oxides easily is not a good candidate for use as a photoelectric thin film.

The CD also needed to be easily switched into and out of the photodiode mode. This was achieved by making a removable photodiode quartz window holder and a separate base which would remain permanently in the CD. This flexibility allows the user to simply remove the photodiode slot cover on the top of the CD and slip in the quartz window holder when this mode was desired. The holder and base are made out of nonconducting Delrin and are shown in figure 2-7. Contact with the quartz window is made by a tinned brass electrode placed between the window and Delrin plate. The electrode extends out of the holder and is folded back to mold to the bottom of the holder. The electrode then makes contact with a brass strip attached to the base by a screw. Good contact is assured by the outer two screws which secure the two pieces snugly together. Thus in less than five minutes the CD can be converted between a photodiode and a pinhole collimated channel electron multiplier (CEM).

In order to accomplish all the desired scientific tasks proposed the CD needed to have some sort of energy selection. For this reason three accelerating screen were mounted in the CD allowing it to be operated as a retarding potential analysers (RPA). The first and third screens are held at ground while the applied voltage is varied on the middle screen. This allows a uniform field to be setup between the screens and prevents any effects from stray fields between the screens and the detector's grounded case. The screenholders are of the same basic design as the photodiode quartz window holder except they are permanently
Photodiode Mount and Base

Figure 2-7
mounted in the CD.

To be able to use a detector to map specific areas of interest it also needs to be well collimated. The best solution to this problem is to collimate a detector using twin pinholes. Using this method, the acceptance angle can be controlled and the energy independent geometry factor can be estimated by

$$G_0 \sim \frac{A_1 A_2}{L^2} \frac{\Delta \epsilon}{\epsilon}.$$  \hspace{1cm} \text{Eqn 2-1}

where $A_1 = A_2$ is the area of the entrance and exit apertures and $L$ is the distance between them. For the case of collimated CEM, the ratio $\Delta \epsilon/\epsilon$ is just unity. As shown in figure 2-6, the CD has three collimation plates in order to better cut done on the amount of reflected UV light entering the spiraltron. Due to the different functions the CD would perform, two sets of collimation plates were made. The first set has an opening area of 1.000 ± .002 mm$^2$ and a half angle of 1.26 ± .06°. The small entrance aperture is ideal for measuring intensity variations as a function of angular position and for detecting small scale irregularity in the beam. The second set of plates were made for the overall mapping of the electron beam and UV source. These plates have a opening of 10.000 ± .002 mm$^2$ and a half angle of 3.94 ± .06°. The plates are mounted to the CD's base via two screws. Like the photodiode, these plates are easily changed with the accuracy of the plates' location being guaranteed by a centering dowel pin.

The final constituent of the CD is the CEM and its electronics. The in-line configuration of the CD led way for the use of a straight compact spiraltron electron multiplier (SEM). The SEM is a Galileo Electro-Optics Corporation model 4219 which has a characteristic electron gain of $2 \times 10^8$ for the recommended operating voltage. The SEM has a dark count rate of less than 0.5 s$^{-1}$ and for counting rates in the $10^4$ s$^{-1}$ range it has an approximate efficiency of 100%. The electronics board used to collect the output of the SEM was originally designated as a back up board for a previous University of New Hampshire rocket flight. Following the successful flight of that rocket, the board was slightly modified for use with the CD. The three basic components on the pulse amplifier are; two transistors, a comparator, and two one-shots. The transistors act as a preamplifier
to increase the pulse coming out of the SEM. This amplified signal is then processed or rejected by the comparator according to a preset pulse height. The two one-shots which complete the circuit prevent any pulse pileup (the triggering of an event in the middle of the sending of a previous event) and relay the output pulse to a counter (the Dot for this testing). A schematic of this process is shown in figure 2-8. The signal out of the comparator is a square wave which triggers the first edge sensitive one-shot. This one-shot then outputs a two micro-second long square wave which both triggers the second one-shot and is fed back to itself. The feedback signal disables the first one-shot for the two micro-second duration to prevent the pulse pileup. Once triggered, the second one-shot sends a one micro-second pulse as output from the board to be counted. It must be noted that the scheme of preventing pulse pileup does cause counting rate compression for randomly arriving events which occur during the forced deadtime. The actual event rate can be retrieved from the compressed count rate using the deadtime correction,

\[ E = \frac{C}{1 - (C \times \tau)} \]  

where \( E \) is the event rate, \( C \) is the count rate, and \( \tau \) is the forced deadtime. Figure 2-8 shows graphically the relation of the count rate to the event rate.

Electron Gun Operational Report

With the means of detection in place, the performance of the electron beam was ready to be tested. A particle beam can be characterized by four parameters: beam energy \( E_b \), energy spread \( \Delta E \), angular spread \( \Delta \theta \), and spatial uniformity. While each of these parameters are not independent of the others, only the beam energy can be set by the user. A spatially uniform beam must first have a illumination source which strikes the photocathode evenly. The uniformity of the UV lamp was mapped using the photodiode function of the calibration detector. The CD was located approximately 1 foot away from the photocathode window. The physical constraints of the positioning table allowed for the scanning of a 6" x 6" grid. With the 10 mm\(^2\) collimation plates in the CD, the area of view on the quartz window would be 1.65" in diameter. Thus the grid was broken into samples every 0.25" giving a measurement of the uniformity of the intensity of the UV source at the
Calibration Detector Electronics

Figure 2-8
photocathode window. The results are shown in figure 2-9 where the counts have been normalized and each contour represents a 10% change in the count rate. Each tick represents one inch in either horizontal or vertical distance. The period of each sample was such that the noise rate was below one percent. The noise rate is calculated to be the square root of the total counts of that sampling period. This figure clearly shows that the photocathode is uniformly illuminated over the majority of its area. The 0.90 contour is found to contain an area of approximately 4" x 4". The drop off of counts near the edge is due in part to the wide acceptance aperture of the CD in this mode of operation and therefore sampling off the lamp.

A photoelectric electron beam has an inherent energy spread and angular spread due to the physical processes which form the beam. The photoelectron is ejected from the photocathode with some initial kinetic energy \( E_i \). Deviation of this direction from normal to the photocathode causes the energy spread and the angular spread. The largest effect comes when the photoelectron is ejected parallel to the photocathode. After the electron has been accelerated perpendicular to the photocathode to the beam energy \( E_b \), an angular spread \( \Delta \theta \approx \tan^{-1}(E_i/E_b)^{1/2} \) exist, where \( \theta \) is measured from the normal to the photocathode (figure 2-10). Because the spread is inversely proportional to the beam energy, as the beam energy is increased, the angular width decreases. Marshall et al. [1986] have shown that the response of a charge particle detector like the CD is related to the angular spread of the beam via the empirical equation

\[
W^2 = W_{ap}^2 + \Delta \theta^2.
\]  

Eqn 2-3

where \( W \) is the observed angular response and \( W_{ap} \) is the angular response of the CD. The observed angular response is defined as the angular range over which the full width at half maximum counts of a constant energy particle beam is recorded by an instrument. Typical calibration energies are such that \( E_i/E_b \ll 1 \), therefore this equation can be approximated by

\[
W^2 = W_{ap}^2 + \frac{E_i}{E_b}.
\]  

Eqn 2-4

Thus \( E_i \) can be determined by plotting the observed angular response \( W^2 \) versus \( 1/E_b \).
Ultraviolet Lamp Intensity
Average Rate (KHz)

Figure 2-9
Figure 2-11 shows four angular scans of the electron beam for four different beam energies (1.5 keV, 2.0 keV, 5.0 keV, and 8.0 keV). The horizontal axis is degrees in pitch and the vertical axis is degrees in roll with the total length of either axis being four degrees. With the 1.000 ± .002 mm$^2$ collimation plates in place, the CD sampled the beam every 0.5° in pitch and roll to make these plots. The counts have been normalized and each contour represents a ten percent change (higher values towards the center, lower values towards the edge). The fifty percent contour is marked on the figure. The square of the observed angular response (the full-width at half maximum of the contour plots) of each data set has been plotted against the inverse of the beam energy in figure 2-12. The solid line represents the best fit line through these points and yields a value of $E_l = 0.45$ eV with a confidence level of $R^2 = 0.997$. Because the main source of energy deviation in the electron beam is due to the electrons which are ejected parallel to the photocathode, the energy spread for the beam can just be taken as $\Delta E = E_i$. As stated above, the angular spread is dependent on the beam energy, for $E_b = 2$ keV the angular spread is $\Delta \theta = 1.6^\circ$.

The uniformity of the electron beam was measured by the CD with its 10.000 ± .002 mm$^2$ collimator plates. Figure 2-13 shows a plot of the count rates recorded at 0.1" intervals on a 5" x 5" grid (tick marks on grid represent 0.5" spacing). The slight gradient
Electron Gun Angular Map
Average Rate (Khz)

a) $E = 1.5 \text{ keV}$

b) $E = 2.0 \text{ keV}$
Electron Gun Angular Map
Average Rate (Khz)

\[ c) \ E = 5.0 \text{ keV} \quad d) \ E = 8.0 \text{ keV} \]
Energy Spread

$E_i = 0.45 \text{ eV}$

$W^2$

$1/E_b$

Figure 2-12
in the vertical direction is due to a time fluctuation of the ultraviolet lamp caused by the varying of the power into the lamp. Following the completion of these test, a new power supply was purchased which regulates the current and voltage such that the power into the lamp is constant. However during the test the power into the lamp was recorded with the other data and effects due to it variation are duly noted. With exception to this small temporal effect, the electron beam is shown to be spatially isotropic. The importance of the choice of acceleration screen was learned during the mapping of the electron beam. Originally the acceleration screen was made of 0.026" diameter stainless-steel wire cloth with an open area of 37.4%. However it was found that the original screen reflected the ultraviolet light back at certain locations of the photocathode causing hot spots in the beam by increasing the intensity of the ultraviolet light at the photocathode. The small open area of the first screen also prevented a large amount of the electrons from passing through the screen. Reflection was prevent in the wire grid screen (the screen now in use) by coating the wires with aerodag. In addition, the larger open area wire grid allows a higher percentage number of electrons to pass through. The one concern of having the wire grid was the possibility of affects due to nonuniform potentials caused by the wire spacing. If the acceleration field was spreading due to this spacing, then the particles should be nonuniformly accelerated and the angular location of the flux peak should shift with respect to the location on the grid. This could be easily seen by comparing two angular maps whose horizontal and vertical position differ by one half the size of the grid spacing, 0.067". Figure 2-14 shows two such plots using the same format described for figure 2-11. The beam's peak changes by less than 0.2° in pitch and 0.1° in roll which is within the errors of the test. With the electron beam working to desired standards, an ion chamber was then added to the system to be used for the calibration of ion detectors.
Electron Gun Uniformity
\[ E = 8000 \text{ eV} \]

Figure 2-13
Electron Gun Spatial Effects
Average Rate (Khz)

a) $E = 8.0 \text{ keV}$

b) $E = 8.0 \text{ keV}$

figure 2-14
Ion Chamber Addition

The ion chamber addition was designed such that it would be an convenient augmentation to the calibration facility. The combination of the photoelectric electron gun and the ion chamber produces an ion source via electron-impact ionization. The ionization chamber is shown in figure 2-15 and the complete ion gun assembly is shown in figure 2-16. The ionization chamber consist of four parts; three acceleration screens, two chamber halves, chamber plate, and the magnetic field coils. The acceleration screens have the same dimensions and wire grid as the electron gun's acceleration screen. The acceleration screen at the entrance of the chamber is mounted in direct contact with the chamber via eight equally spaced screws. The acceleration screen at the exit of the chamber is electrically isolated from the chamber by an 1/8" thick piece of Delrin and is fastened to the chamber via eight equally spaced Delrin screws. The two chamber acceleration screen's each are mounted on two inch high piece of Macor to insure their electrical isolation from the chamber plate. The third acceleration screen is grounded by mounting it directly to the chamber plate.

The two chamber halves were milled from a single piece of aluminum stock. The inner radius of the chamber is 7.5", the outer radius, where the chamber is bolted together in eight places, is 10.50", and when assembled the chamber measures 4.25" in length. The ionization gas is introduced into a collimation aperture at four 1/8" entrances equally spaced about the chamber radially. A cross-sectional view of the collimation aperture is given in figure 2-17. The pressure range at which the ion gun operates is such that the gas has a molecular flow free of any viscous effects [Leybold-Heraeus 1989]. When a particle is moving in molecular flow it can be treated like a billiard ball having elastic collisions. The collimation aperture was designed to insure that as the neutral particles left the aperture and entered the ionization chamber they should have velocities perpendicular to the chamber wall. By limiting the ionization region to a small length in extraction direction, the amount of energy spread in the beam due to the small electric field gradient across the ionization chamber can be negated.

The chamber plate was designed to conveniently switch from to the existing electron calibration setup to an ion calibration setup and to be able to store it easily when not in use. The ionization chamber assembly is attached to the mounting plate via the two Macor
Ion Chamber Addition

A: Entrance Acceleration Screen
B: Ionization Chamber
C: Exit Acceleration Screen
D: Ground Screen

☐ Aluminum
☐ Macor
■ Delrin

Figure 2-15
Ion Gun Assembly

Figure 2-16
Ion Chamber Diffusion Aperature
standoffs. The mounting plate itself is 13.00" by 8.75". When switching from the
electron calibration setup to ion calibration setup the acceleration screen is first removed,
then the mounting plate is then placed on the electron gun frame as shown in figure 2-16.

The final component of the ion chamber addition is the magnetic field coils. When a
large magnetic field is applied axisymmetric to the incoming electron path in a ionization
chamber, the number of neutrals ionized increases because the path length of electrons in the
chamber are then longer. A solenoidal field was produced by having wrappings consisting
of two 100' sections of 26 gauge stranded wire with a section wrapped around each half of
the chamber halves. It was calculated that a current of 2 amps would set up a magnetic flux
of approximately 15 Gauss. The addition of the magnetic field to the ionization chamber
was seen to have a substantial affect in increasing the number of ions produced. This will
be discussed further in the next section.

**Ion Gun Operational Report**

Unlike the relative simple process which produces a photoelectric electron beam, an
electron-impact ion source requires the fine tuning of its components. The four elements
that define the ion beam are; the electron energy, the chamber pressure, the applied
magnetic field, and the ion energy. The electron energy is determined by the voltages
applied between the photocathode (V_{pc}) and the ionization chamber entrance (V_{ent}). The
electron energy at which singly charged ions are produce with maximum efficiency has
been reported to be 70 eV [J. H. Moore et al 1983]. Tests were performed to find the
optimum electron energy. The ion energy and chamber pressure were kept constant during
the test at $E_e = 1972$ eV and $7.5 \pm .50 \times 10^{-6}$ Torr. The flux was seen to rise sharply with
the increasing electron energy and peaks at $E_e = 50$ eV after which it declines at a slower
rate.

Two externally controlled elements which affect the ion flux are the ionization chamber
gas pressure and the ionization magnetic field strength. The ionization chamber gas
pressure is regulated using a Vacoa metering valve. The pressure of the ionization chamber
is measured as part of the whole system by the vacuum system's ion gauge. The metering
valve allows for the pressure of the system to incremented or decremented by as little as $1 \times
10^{-6}$ Torr. The variation of ion flux detected by the CD as the pressure was increased is
**Figure 2-18a**

\[ y = 16.665 + 5.5714 \times 10^6 x \]

\[ R = 0.99354 \]

**Figure 2-18b**

\[ y = 19.672 + 14.397 x \]

\[ R = 0.98058 \]
shown in figure 2-18a. As is expected, a linear relation is shown by this graph. The failure of this relation to return to zero counts for zero pressure is due to the ambient gas present in the vacuum chamber. In order to minimize the risk of a high voltage arc in the instruments, the pressure in the chamber is never allowed to raise above $2 \times 10^{-5}$ Torr.

The strength of the magnetic field in the ionization chamber affects the ionization rate by changing the path length of the electrons in the chamber. The ion flux was recorded for varying magnetic strengths in the chamber and the results are plotted in figure 2-18b. The ion flux varied linearly with the increase of magnetic field with a slight decrease in the highest values of the magnetic field.

An electron impact ion beam does not have a simple empirical formula which describes its angular width and energy spread. However, the ion beam should behave similarly to the electron beam in that the angular spread of the ion beam is due to any initial transverse velocity. As was shown for the electrons, the angular width of the beam in this case should also decrease as the energy of the beam increases. Figure 2-19 shows the angular spread of the ion beam of energy $E_f = 1972$ eV is $5.75^\circ$ in roll and $4.75^\circ$ in pitch for full width at half maximum (the counts are normalized and contours are spaced every 10%).

The RPA mode of the CD and a sweeping capped hemispherical analyzer (CHA) were used to help understand the energy spread of the ion beam. The voltage on the RPA screen was stepped and the flux detected was recorded. The ionization chamber's entrance voltage, 1972 V, and applied RPA voltage were measured by a Keithley multimeter. Similarly, the voltage across the parallel plates of the CHA was stepped and the flux detected was recorded. The results are shown in figure 2-20. It should be noted that the RPA detects the integral of the flux above the applied voltage while the CHA detects the actual flux at an energy. The relative counts show that the RPA observed 80% of the total flux within 10% of the selected energy (1972 eV). The CHA observed a 13% energy band for full width at half maximum. The energy spread is within the detector's energy resolution and therefore it can only be stated that the ion beam resolution must be below 13%.

As was the goal of the electron gun, the desired product of the ion gun was a source that was narrow in energy and angular width, a flux level usable in calibration, and a source as broad as possible. Most of this section has focused on the optimizing of external
Ion Beam Angular Map

E = 1972 eV
Average Rate (KHz)

Figure 2-19
Figure 2-20

Ion Beam Energy

Relative Counts

Energy (eV)
parameters to produce the maximum ion flux. However, it was found that the beam width is also affected by the variation of certain parameters. The ion beam uniformity was measured by the CD with its 10.000 ± .002 mm$^2$ collimator plates and is shown in figure 2-21. The plot is 3" on a side and the CD sampled every 0.1" to make the plot. The beam measures 1" on a side for full-width at half maximum. The parameters varied to find the greatest width are the magnetic field strength and the potential difference across the ionization chamber. The geometry of the ionization chamber's magnetic field and applied potential is shown in figure 2-22. These parameters were chosen as candidates because they can cause the ion beam to be focused towards the middle of the ionization chamber. The rigidity of the low energy electron entering the strong ionization magnetic field would cause these electrons to follow the fringe magnetic field lines toward the center and thus limiting the volume in which the ions are produced. The geometry of the ionization chamber can also cause the ions to be accelerated radially inward by the chamber potential. As is shown in figure 2-22, the cylindrical ionization chamber (and entrance acceleration screen) is held at a potential of $V_{in}$ while the exit acceleration screen is held at a potential of $V_{out}$.

<table>
<thead>
<tr>
<th>$\Delta V$</th>
<th>$V_{in}$</th>
<th>$V_{out}$</th>
<th>B</th>
<th>$\Delta x$</th>
<th>$\Delta y$</th>
</tr>
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<td>66</td>
<td>1972</td>
<td>1906</td>
<td>0.0</td>
<td>0.76</td>
<td>0.75</td>
</tr>
<tr>
<td>25</td>
<td>1972</td>
<td>1947</td>
<td>0.0</td>
<td>0.80</td>
<td>0.76</td>
</tr>
<tr>
<td>5</td>
<td>1972</td>
<td>1967</td>
<td>0.0</td>
<td>0.92</td>
<td>0.86</td>
</tr>
<tr>
<td>0</td>
<td>1972</td>
<td>1972</td>
<td>0.0</td>
<td>0.96</td>
<td>0.92</td>
</tr>
<tr>
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<td>1967</td>
<td>9.7</td>
<td>0.96</td>
<td>0.96</td>
</tr>
<tr>
<td>0</td>
<td>1972</td>
<td>1972</td>
<td>9.7</td>
<td>1.00</td>
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</tr>
<tr>
<td>0</td>
<td>1972</td>
<td>1972</td>
<td>16.4</td>
<td>1.06</td>
<td>1.05</td>
</tr>
</tbody>
</table>

Table 2-1

This geometry will set up an electric field which will cause the ions to be accelerated radially inwards as well as out of the chamber. The results of the measurements of the beam size as function of these two parameters is given in table 2-1 (where $\Delta V = V_{in}$).
Ion Beam Uniformity

$E = 1972 \text{ eV}$

Average Rate (KHz)

Figure 2-21
Magnetic Field Configuration

Potential Configuration

Figure 1-22
The beam was measured for varied potentials at a fixed magnetic field. The test showed that indeed when the potential across the ionization chamber was raised the beam narrowed. However when there was no potential difference across the chamber, the beam was still only ~1" in diameter. The magnetic field results showed the opposite results than expected. As the magnetic field was increased, the beam width actually increased slightly. This was most likely caused by the electron source being located close enough to the ionization chamber that as the current to produce the magnetic field was increased, a portion of the magnetic field penetrated the photocathode where the electrons are produced. In any case, the multiple attempts to produce a broad ion beam failed. However, the 1" diameter beam is larger than the entrance apertures of the chapped hemispherical analysers. Thus this beam has been found to provide an adequate source for the calibration of these detectors.
METAL BLACK COATINGS

When a compromise of data occurs during a flight, the top priority of an experimentalist is to prevent the same from happening on future flights. Such was the case with the UV contamination on flight 35.017. Flight 35.017 was launched January 19, 1988 from Poker Flat, Alaska at 08:40:04 UT. The payload traversed through three active discrete auroral arcs. During these times the electrostatic instruments onboard the flight registered false counts from the ultraviolet emissions from the auroral arcs. It was determined that the counts were due to the ultraviolet emission because the contaminated data was spin modulated and had no energy dependence. It is readily known that instruments flown on satellites are often coated with what is referred to as gold black. It was also known that this process was not done wide spread in the commercial world and therefore is a costly operation. The process of applying black metal coatings was first developed in the 1930's (Pfund 1930, Pfund 1933) for the coating of radiation thermocouples. Further work was done in the following years by Louis Harris (Harris et. al. 1948, Harris and Beasely 1952, Harris and Loeb 1953) with his primary focus on gold black. Harris concluded his work with a summary of different metal blacks and their properties (Harris 1967). Both of these men used the same basic procedure to produce a black metal. The process involved evaporating a metal at high vacuum and then forcing it to condense on the desired surface by raising the pressure of the chamber with a backfill gas. For obvious reasons, the formal name of this procedure of applying a metallic coating is known as vacuum evaporation. Metals blacks are thin metallic deposits with finely divided states which have the properties of low reflectance and high absorption. The low reflectance of visual light cause the deposits to appear black.

When choosing the type of metal to use for the coating, several factors must be considered. Galvanic corrosion can set in when two unlike metals are in contact. This process is caused by a galvanic current which is set up when two dissimilar metals are in contact and are exposed to an electrolyte (such as air or water). This current causes a corrosion on the anodic metal. It was found (Corrosion 2 14 : 31) that one of the best noncorrosive metal coatings was zinc. While zinc can be used to form a black zinc coating,
it was difficult to work with because of its lack of ductility. Copper, on the other hand, is easy to work with in its wire form but will cause galvanic corrosion when placed in contact with aluminum. However, the ESAs which were to be coated also were to house a delicate microchannel plate (MCP). In order to assure consistent gain, these MCPs must be kept under constant vacuum or in a nitrogen purge to avoid the absorption of water vapor present in the air. Thus the ESA are kept under vacuum or nitrogen purge, meaning the copper and aluminum are not exposed to an electrolyte but during brief time periods. It was felt that these minimal time periods (on the order of minutes) would not (and did not) cause any sort of detectable corrosion.

Experimental Setup

The experimental setup for the black coating of the detectors is shown in figure 2-23. The entire processes is contained within a vacuum bell jar with a bottom radius of eighteen inches. The vacuum system is composed of a roughing pump, which reaches the millitorr range, and an oil diffusion pump for high vacuum. The crucial mechanical part of the vacuum system, seen in figure 2-23, is the electrical feed-through with two degrees of freedom. The feed-through arm can be both adjusted in height and rotated. This allowed for the needed precise positioning of the filaments during the actual process of metallic black coating.

Standardized Procedure

The process of applying a metallic black coating to a desired surface requires two stages. Before either stage can be performed some basic preparation must be completed. While some of these steps are required for the coating of any surface, this procedure has been developed for the express use in coating ESAs. This is significant because, as described in Section 1, the ESA must produce an electric field between its parallel plates. Thus any coating which absorbs ultraviolet must be a conductor, which metal blacks are, and when applied, must also produce a uniform electric field across these parallel plates. In order to insure this last demand, good contact between the conducting surface of the ESA and the coating is needed. Shortly before the piece is to be plated, it is sand-blasted to remove the build up of nonconducting aluminum oxide. The piece is then cleaned in a heated ultrasonic freon bath. This removes any small particles on the surface as well as
Diffusion Vacuum System

Figure 2-23
other out-gassing materials that have been deposited on this surface. The final step of preparation of the surface to be coated is to allow it to cool to room temperature.

The routine of evaporating the copper requires the preparation of both the copper and the filament upon which it is melted. The vaporization filament must have a high melting point in order to avoid contaminating the coating with filament vapor. A 0.010" diameter molybdenum wire was chosen for this purpose. The length of the filament is dictated by the current source. In order to melt the copper, a current of at least four amps must pass through the filament. It was found that the ideal length for the molybdenum filament was 15 centimeters. The shape of the filament was also found to be of great importance. Ideally, the filament could heat some container holding an amount of copper. Thus the copper could be melted and vaporized without any loss. However this would require a much more powerful current source than what was available at the time. For this reason, the restriction of melting and vaporizing the copper directly on filament was the burden. When this approach is taken, it must be remembered that the current will preferentially pass through the lower resistance copper instead of the molybdenum filament. Thus shorting out the molybdenum filament by the copper strands must be avoided. It also must be realized that when the copper melts it becomes a liquid that must remain on the filament long enough for all the copper to melt and then be vaporized. This requires the balance of the liquid copper's gravitational force with its surface tension which holds it to the filament. Therefore only a limited amount of copper can be vaporized on each filament. Figure 2-24 shows the design of the filament and copper strand which was found to perform the best. A single strand is hung in each of the V portion of the filament. The .015" diameter copper wire is cut to a length of 1 1/2 centimeters and then twisted into the shape shown in the lower portion of figure 2-24. This combination allows for the desired amount of copper to be vaporized by using several copper drops while not causing an electrical short. There is always a chance that a drop may fall before it is vaporized due to some miscellaneous motion on or around the vacuum system, but it was found that using these two configurations, the drop was vaporized nearly ninety percent of the time.

In order to insure the best contact between the copper black and the surface on which it is coated, a layer of shiney copper is applied to the aluminum analyzer plates. A shiny metal is the term given a vacuum evaporation coating in which the metal is allowed to
Blacking Filament and Strand

Figure 2-24
condense on the desired surface in a high vacuum. The lack of collisions with an inert gas, as described earlier, enables the condensing copper to form a uniform surface of metal. This surface is much more suited to bonding with a different metal than a black metal because of its much more stable environment. The surface is also highly reflective and thus named shiney metal. The regiment required to achieve the coating of shiney copper is very straightforward.

The desired piece must first be allowed to cool in order to insure a conducive environment for condensation. It is then place in the vacuum system and pumped down to the range of $10^{-5}$ Torr. Because this process is conducted at high vacuum, the mean free path of the vaporized particle is greater than the size of the vacuum chamber. This implies that the position of the surface needs only to be within some reasonable distance and that the bell jar will also be coated with shiney copper. It should be noted however, that the filament should not be placed directly over the piece being coated in order to avoid the case of a melted drop falling upon it. After the desired pressure has been reached, a current of four amps was placed through the filament. After all of the strands have melted and formed liquid drops, the current is increased to vaporize the metal. Visual inspection of the filament will show when all of the copper has been vaporized. After the current supply has been turned off, the chamber is then allowed to return to room pressure. The thickness of the layer of shiney copper is controlled by the amount of copper used. If a thicker coating is required, then additional coats may be added. It was found that one filament coating was sufficient for covering the ESA's conducting plates.

The second stage involves the actual application of the copper black. As in the first stage, the piece must be placed in the vacuum chamber and pumped down. However, unlike before, the copper black is condensed at a much higher pressure causing smaller mean free paths. It is therefore of critical importance to place the piece three centimeters from the filament. Placing it closer is not advised due to the thermal speeds at which the vaporized gas have initially and also effects from the heating of the filament. Of equal importance is the orientation of the filament with respect to the piece which is to be coated. It was found that the copper black was most absorbent when applied in the same direction as the trajectory of the light which is to be absorbed. This configuration is shown in figure 2-25. Data to support this claim will be presented in following paragraphs.
Blacking Configuration

Figure 2-25
After the piece has been suitably positioned, the chamber is again pumped down to the 10^{-5} Torr range. As in the previous stage, the filament is then heated by running 4 amps of current through it. It is important not to have an excessive amount of current through the wire at this time so that the copper strands will just melt and not vaporize. When all of the strands have formed liquid drops, the pressure is quickly raised to fifty to seventy milliTorr by the introduction of a backfill gas. The copper then randomly condenses on the analyzer forming the black coating. The choice of the backfill gas and the coating metal dictate at what pressure this process should occur. The main process controlling the formation of black metals is the inelastic collisions between the backfill gas and the vaporized metal allowing the metal to cool down and condense. Thus zinc requires a higher pressure than copper to form its black coating while similarly more helium (a higher pressure) is required to form a black coating than when using nitrogen as the backfill. It is advised to apply several coating of the black metal because of settling of coating due to the random nature of it surface and to avoid any effects due to oxidation from contact with the atmosphere.

Ultraviolet Test Results

The optical properties of black metals were the prime concern of the early studies of Pfund and Harris. However, because their work dealt with the coating of radiation thermocouples, their focus was mainly on reflectance and transmittance of the infrared and far infrared. Work on the reflectance of UV by certain black metals was done by M. C. Johnson (1968). Johnson measured the reflectance of the black metals gold, nickel and silver. The samples were illuminated in a goniometer chamber by incident radiation of 1216 Å. The reflectance was measured by two Channeltron multipliers, one mounted normal to the sample's surface and the second in the same plane but at angle of 45°. A summary of his results are shown in table 2-2. The angle of incidence is with respect to the normal of the specimen and the hemispherical reflectance is the integrated total reflected intensity assuming cylindrically symmetrical intensity distribution. As was noted in a previous section, the CHAs were coated in manner such that any incident UV would have a small angle of incidence and thus the smallest reflectance. While these results were reassuring, Johnson had not tested black copper. With the help of Professor Roy Torbert, a sample of
## Black Metal UV Reflectance

<table>
<thead>
<tr>
<th>Surface</th>
<th>Angle of Incidence</th>
<th>Hemispherical Reflectance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Black-Gold</td>
<td>15°</td>
<td>0.765%</td>
</tr>
<tr>
<td></td>
<td>45°</td>
<td>0.871%</td>
</tr>
<tr>
<td></td>
<td>60°</td>
<td>1.633%</td>
</tr>
<tr>
<td></td>
<td>75°</td>
<td>2.34%</td>
</tr>
<tr>
<td>2. Black-Silver</td>
<td>15°</td>
<td>1.77%</td>
</tr>
<tr>
<td></td>
<td>45°</td>
<td>1.95%</td>
</tr>
<tr>
<td></td>
<td>60°</td>
<td>2.58%</td>
</tr>
<tr>
<td></td>
<td>75°</td>
<td>3.1%</td>
</tr>
<tr>
<td>3. Black-Nickel</td>
<td>45°</td>
<td>11.1%</td>
</tr>
</tbody>
</table>

Table 2-1

Black copper was sent to NASA's Goddard Space Flight Center (GSFC). GSFC's J. Heaney and R. Keski-Kuha made measurements using similar techniques as Johnson, but using incident radiation of 584 Å. Their results are shown in figure 2-26 along with their results of other materials. The black copper has the lowest reflectance of any material measured so far at GSFC and the reflectance was so weak that it approached the instrument's noise limit (Heaney and Keski-Kuha private communicate). With these facts on black metals and specifically black copper, it is felt that the previous presented techniques are a solid and feasible method of protecting an ESA from being contaminated by UV radiation.
Figure 2-26
Calibration of Flight 35.020's Particle Package

With the calibration facility in place and the black coating of the capped hemispherical analysers complete, the particle package for flight 35.020 was ready for its preflight calibration. The main purpose of the preflight calibration is to be able to understand how an instrument will react to a series of environments. Therefore when similar environments are encountered during an experiment, the signatures in the data are then recognizable. Three tests have been devised to best understand the response of the capped hemispherical analysers. These tests involve measuring: the energy bandwidth as a function of the particles' azimuthal acceptance direction, the energy bandwidth as a function of the particles' polar acceptance direction, and the azimuthal imaging of the detector. The orientation of the HEEPS instrument for the calibration tests and the angles referenced in the follow sections are given in figure 2-27 and follow the convention set by Pollock [1987]. The broad beam source and automated positioning table allow for the gathering of this information in a convenient and efficient manner that was not possible before the construction of this system.

Azimuthal Imaging Test

The procedure in which the azimuthal imaging of the capped hemispherical analyzer is determined is similar to that described in Section I during the discussion on the HEEPS accumulation bins. In all of the calibration tests the capped hemispherical analyzer was mounted on the positioning table such that the detector's acceptance plane was perpendicular to the roll axis. For the present test the capped hemispherical analyzer sampled the electron beam (which was held at a constant energy) every 2.5° in azimuth. The constant flux of the electron beam also enabled the use of equal sampling periods (as opposed to sampling a fixed number of counts as in the calibration of flight 35.017). Figure 2-28 shows the data from the azimuthal calibration of one of the electron capped hemispherical analysers. This specific electron HEEPS had an 330° azimuthal acceptance plane and was swept in energy. The three gaps in the data at approximately -105°, 40°, and 130° are due to blind spots in the instrument. The linear nature of the data reveals that the
HEEPS
ENTRANCE APERTURE

Figure 2-27
ARCS 4
Azimuthal Image Calibration Data

Figure 2-28
detector is working as expected with an imaging bin having a half angle view of approximately 5°. The calculation of the exact determination of the azimuthal look angles will follow the procedure used for the HEEPS on flight 35.017 and is described in Section 1 in the Data Reduction part.

Azimuthal Angular Energy Bandwidth

The physical geometry of the capped hemispherical analyzer requires the testing of the energy bandwidth as a function of azimuthal position. Electrostatic analysers work on the premise of selecting a certain energy per charge particle by having that particle experience a centripetal force due to a potential across a pair of curved plates and therefore causing the particle to travel through these plates. Numerically this can be expressed as:

\[ E \approx \left( \frac{R_0}{R_2 - R_1} \right) \times \left( \frac{V_2 - V_1}{2} \right) \]

where \( R_0 \) is the mean radius of the path the particle takes through the plates, \( R_1 \) is the radius of the inner curved plate, \( R_2 \) is the radius of the outer curved plate, \( V_1 \) is the voltage applied on the inner plate, and \( V_2 \) is the voltage applied to the outer plate. Thus a change in the gap between the curved plates (\( R_2 - R_1 \)) will affect what energy per charge particles are accepted. In the case of simple electrostatic analyzer, such as the CESA instrument discussed in Section I, this gap has a predetermined spacing that is ensured by side supports which attach directly to the plates. The capped hemispherical analyzer cannot have this type of support because it requires the plates consist of two concentric hemispheres. Any slight deviation (as small as a few thousands of an inch) from being perfectly aligned will cause variations in the energy per charge acceptance in the azimuthal direction. Figure 2-29 give the results of the calibration test of the energy bandwidth as a function of azimuthal position. The HEEPS instrument was held at a fixed energy step (constant potential across the plates) while the electron gun energy was swept from -30% to +30% of the fixed energy value (3970 eV in this case). The HEEPS instrument was then rotated by a increment of 2.5° in azimuth and then the process was repeated. The blind spots are once again clearly visible at approximately -105°, 40°, and 130°. It is also clear from this data
Figure 2-29

ARCS 4
Azimuthal Energy Bandwidth

Percent of Gun Energy (% eV)

Roll (deg)

Average Rate (KHz)
that indeed the hemispheres are not concentric. While the electrons entering the HEEPS at 0° roll have their maximum counts centered about the selected energy, the maximum counts at the azimuthal angles of ±180° are found to be centered about the +3% level. Thus these azimuthal imaging bins would preferably select electrons with the energy of ~4090 eV. This data also shows the finite spread of particle energy that is allowed into the detector for a fixed energy step. While the center of the peak is seen to vary in azimuth, the full width at half maximum is also seen to remain constant over the azimuthal range at approximately 10% of the selected energy. Therefore the calibration test of the energy bandwidth as a function of azimuthal position gives the experimenter a better knowledge of overall energy response of the HEEPS instrument as well as the variation of energy selection due nonconcentric hemispherical plates in the HEEPS.

**Polar Angular Energy Bandwidth**

The capped hemispherical analyzer is also seen to have a finite energy bandwidth due to the variation of the incident polar angle of particles. Figure 2-30 illustrates the energy bandwidth as a function of polar angle. The HEEPS instrument was again held at a fixed energy step while the electron gun energy was swept from -30% to +30% of the fixed energy value (again 3970 eV). The HEEPS instrument was then stepped by a increment of 1.0° in pitch (the polar angle direction) and the process was then repeated. This plot reveals that the peak electron flux is centered on a polar angle of approximately 88.5° and at an energy of 2% less than the fixed energy value. The plot also shows that particles transmitted with polar angles greater than 90° have larger energies and that those with polar angles less than 90° are at smaller energies. This result agrees with that found by Pollock [1987] in which Pollock showed that this effect was due to the relationship of the field strength required for the deflection of the particles in the applied electrostatic field as a function of incident polar angle. One difference between the results reported in this thesis and that found by Pollock was that Pollock found the particle flux peak at a polar angle of approximately 93°. The difference of these two findings show that different capped hemispherical analysers have similar traits (i.e. same type energy bandwidth response to varying polar angle) but have distinct specific features (i.e. exact polar angle where the particle flux is maximum).
Figure 2-30

ARCS 4
Polar Energy Bandwidth
Average Rate (KHz)

Percent of Gun Energy (% eV)

Pitch (deg)
Pollock [1987] also points out that this measurement is vital for determining the energy-independent geometry factor. The energy-independent geometry factor is defined as:

$$G_0 = \delta A (\delta \Omega \delta e/e)$$  \hspace{1cm} \text{Eqn 2-6}$$

where $\delta A$ is the effective area of the entrance aperture, $\delta \Omega$ is the angular field of view of the instrument, and $\delta e/e$ is the fractional energy bandpass of the instrument. For the individual bin geometry factor the quantity $\delta \Omega$ can be expanded to be $\delta \phi \sin(\theta) \delta \theta$ which when incorporated into eqn 2-6 yields the individual bin geometry factor:

$$G_{oi} = \delta A \delta \phi \left( \sin(\theta) \delta \theta \delta e/e \right)$$  \hspace{1cm} \text{Eqn 2-7}$$

Pollock shows that when the approximation $\sin(\theta) \sim 1$ is taken, then the quantity $\left( \sin(\theta) \, d\theta \, de \right)$ can be estimated as either the surface area enclosed by the 50% contour in figure 2-30 or as the volume under the surface of the entire contours. Thus a calculation of the energy independent geometry factor can be made from the results of this test.

In order to make this calculation, the value of the effective area of the entrance aperture $\delta A$ must be known. Experimentally this can be determined by a test in which the response of the detector count rate is measured for increasing incident flux [Pollock 1987]. However the present calibration facility is not equipped to perform such a test. Instead, if the assumption is made that the effective area of the entrance aperture is proportional to the actual area of the entrance aperture, then $\delta A$ can be found from scaling the value determined by Pollock [1987]. Therefore the effective area of the entrance aperture $\delta A$ should be:

$$\delta A_{35.020} = A_{35.020} \frac{\delta A_{\text{proto}}}{A_{\text{proto}}} = 4.97 \frac{4.80^{+1.0}_{-3.4} \times 10^{-3}}{1.45} \text{cm}^2$$  \hspace{1cm} \text{Eqn 2-8}$$

$$= 1.65^{+0.24}_{-1.17} \times 10^{-2} \text{cm}^2$$
where the subscript proto refers to the results found by Pollock [1987]. The area enclosed by the 50% contour in figure 2-30 is found to yield a value of

\[
\langle \sin(\theta) \, d\theta \, d\epsilon \rangle = 9.43 \times 10^{-2} \text{radian-keV}.
\]

Eqn 2-9

From figure 2-30, the peak value of the plot is found at \( \epsilon = 3.891 \) keV and estimating the azimuthal bandpass as \( \delta \phi = 0.26 \) radians will yield a individual bin geometry factor when substituted into equation 2-7 of

\[
G_{oi} = 1.04 \pm 0.22 \times 10^{-4} \text{cm}^2\text{-ster-keV}\text{keV}^{-1}.
\]

Eqn 2-10

Comparison of this to the method used in Section I to calculate the individual bin geometry factor of the HEEPS flown on flight 35.017 is useful. The geometry factor of the total HEEPS instrument has been shown to be in equation 1-21 to be

\[
G_0 = 2R_1^2 \times \frac{G'}{R_1^2}.
\]

Eqn 2-11

Using the method described in Section I to determine the quantities in equation 2-11 yields a total geometry factor of

\[
G_0 = 2.70 \times 10^{-2} \text{cm}^2\text{-ster-keV}\text{keV}^{-1}.
\]

Eqn 2-12

Taking the approximation that the accumulation bins are 5° in angular width, then the individual bin geometry factor can be estimated as:

\[
G_{oi} = G_0 \frac{5}{360^\circ} = 3.75 \times 10^{-4} \text{cm}^2\text{-ster-keV}\text{keV}^{-1}.
\]

Eqn 2-13

Thus the two values of the individual bin geometry factor are not found to be in good agreement. The individual bin geometry factor in equation 2-10 was found by scaling the
effective area determined by Pollock [1987]. While scaling methods have been useful in
determining other calibration quantities, in this case a change in the electronics design
between the prototype HEEPS of Pollock and the HEEPS for flight 35.020 means a new
saturation test should be performed. The individual bin geometry factor calculated in
equation 2-10 can serve as a first order approximation knowing that the actual effective area
of the HEEPS from flight 35.020 should be larger than the prototype HEEPS because of
the improved electronics and therefore increase the individual bin geometry factor.

Along with being used to calculate the individual bin geometry factor, the polar angle
energy bandwidth calibration data can be used to produce more realistic phase space
distribution plots. Each of the individual accumulation bin look angles can be assigned by
the values found in the azimuthal imaging test and the polar angle determined by the present
test. With these accurate look angles, the azimuthal variation of energy bandwidth can be
implemented to yield the best possible velocity vectors for the incoming particles and
therefore produce the most realistic phase space distribution function.
Appendices
Appendix A

Integrated Electron Energy Flux

The integrated electron energy flux ($I_e$) is defined as:

$$I_e = \int f(v) \frac{1}{2} mv^2 \cdot d^3v,$$

Eqn A-1

where $f(v)$ is the electron single particle distribution function, $1/2 \, mv^2$ is the electron energy, and $v \cdot d^3v$ is the velocity through the surface oriented perpendicular to the magnetic field. The relation of the various terms of the integrated electron energy flux to the measured and known quantities of the CESAs is easily found when approached in a step by step manner. The single particle distribution function has been shown [see Morgan 1976] to be:

$$f(v) = \frac{m^2}{2} \frac{J'}{E},$$

Eqn A-2

where $J'$ is the differential directional particle flux, $m$ is the electron mass, and $E$ is the energy at which the electron is detected. Further we know that the differential directional particle flux can be calculated from:

$$J' (v) = \frac{R}{G_0 \, E},$$

Eqn A-3

where $R$ is the detected counts per time interval and $G_0$ is the energy independent geometry factor of the CESAs.

The orientable surface term can be reduced to:
\[ \mathbf{v} \cdot d^3\mathbf{v} = v^3 \sin \theta \cos \theta \, d\theta \, d\phi \, dv. \]  
Eqn A-4

Noting that \( E = \frac{1}{2} m v^2 \), then the differential element \( dv \) can be expressed as:

\[ dv = \frac{dE}{mv}. \]  
Eqn A-5

Substituting these into equation A-1 yields:

\[ I_e = \int \frac{m^2 R}{2G_0 E^2} E v^2 \sin \theta \cos \theta \, d\theta \, d\phi \, \frac{dE}{m} \]

\[ = \int \frac{R}{G_0} \sin \theta \cos \theta \, d\theta \, d\phi \, dE. \]  
Eqn A-6

The assumption is then made that there is no azimuthal dependence and therefore the integral over the azimuthal component is just \( 2\pi \). Furthermore the integral over the energy is replaced by a sum and reduces the equation to:

\[ I_e = \frac{2\pi}{G_0} \int \sin \theta \cos \theta \, d\theta \, \sum_i R_i \Delta E_i, \]  
Eqn A-7

where the indice \( i \) indicates energy energy step. From the calibration data of the CESAs it is known that the energy bandwidth is ten percent of the selected energy and the numerical value of the energy independent geometry factor is \( 5 \times 10^{-5} \) cm\(^2\) ster keV/keV. Thus the sum over \( R_i \Delta E_i \) can just be reduced to a sum of the product of the values of the energy step \( E_i \) and the counts \( R_i \) at that energy step. The assumption is also made that CESA1 is detecting mostly field-aligned electrons (pitch angle range \( 0^\circ-10^\circ \)) and CESA2 is detecting the rest of the down flowing electrons (pitch angle range \( 10^\circ-90^\circ \)). Therefore the integrated electron energy flux reduces to:
\[ \int_{0}^{\pi} \frac{10}{2\pi} \sin \theta \cos \theta \, d\theta = \text{I}_\text{Ces} \]

and

\[ \int_{0}^{\infty} \frac{10}{2\pi} \sin \theta \cos \theta \, d\theta = \text{I}_\text{Ces} \]
Appendix B

Ion Distribution Function Calculation and Display

The single particle distribution function of the ions is calculated in the same manner as the electron single particle distribution function discussed in the previous appendix. That is the ion distribution function is defined as:

\[
f(v) = \frac{m^2}{2E} J',
\]

Eqn B-1

where \( J' \) is the differential directional particle flux, \( m \) is the ion mass, and \( E \) is the energy at which the ions are detected. Further we know that the differential directional particle flux can be calculated from:

\[
J'(v) = \frac{R}{G_0 E},
\]

Eqn B-2

where \( R \) is the detected counts per time interval and \( G_0 \) is the energy independent geometry factor of the instrument. With the advent of the capped hemispherical analyzer, the first high time resolution complete phase space plots can be made. That is the HEEPS' 64 accumulation bins allow for the sampling of a large surface in velocity phase space every energy sweep. With this system the distribution is found for 2048 points in phase space every sweep. The display of this data is therefore no easy task. Because the distribution function is a function of the vector velocity, one of the distribution function's components must be collapsed in order for it to be visually displayed. Examples of different collapses and the calculation of the velocity vector are given in the following paragraphs.

In the pitch angle system, describe in Section I-B, the pitch angle \( \alpha \) of a particle (the angle between a particle's velocity vector and the magnetic field) is determined from:
\[ \alpha = \arccos \left( \frac{\mathbf{B} \cdot \mathbf{u}_i}{|\mathbf{B}|} \right) \]  
Eqn B-3

where \( \mathbf{B} \) is the magnetic field measured by the onboard magnetometer and \( \mathbf{u}_i \) is the acceptance bin's unit vector determined from preflight calibration. This pitch angle is then used to define the velocity of the particle by:

\[ v_\perp = \sqrt{\frac{2E}{m}} \sin \alpha \]

\[ v_\parallel = \sqrt{\frac{2E}{m}} \cos \alpha , \]

Eqn B-4

where \( E \) is the energy of the ion, \( m \) its mass, and the perpendicular and parallel are in reference to the local magnetic field. When a particle velocity is thus determined, an assumption of azimuthal symmetry is automatically forced into the distribution function. This comes about because pitch angle is limited to values between 0 and \( \pi \) and therefore the perpendicular velocity must always be positive. The assumption of azimuthal symmetry causes the collapse of that component in the distribution function or schematically folding the data from a cylinder unto a plane (figure B-1a). This is a valid procedure when the data of concern is of energies much higher than the ram velocity. However, the thermal energies of \( \text{H}^+ \) and \( \text{O}^+ \) are comparable or well below the ram velocity and thus require a system which has no inherent symmetry.

A second coordinate system that has a distinct ram and antiram direction and also includes the magnetic field as one axis is the \( \text{nrb} \) coordinate system. The unit vectors for this system are defined by:

\[ \hat{\mathbf{b}} = \frac{\mathbf{B}}{|\mathbf{B}|} , \]  
Eqn B-5

\[ \hat{n} = \frac{[\mathbf{V}_r \times \mathbf{B}]}{|\mathbf{B}| |\mathbf{V}_r|} , \]  
Eqn B-6
## Coordinate System Presentations

<table>
<thead>
<tr>
<th>Data System</th>
<th>Presentation</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
<td>Averages together the azimuthal component</td>
</tr>
<tr>
<td><img src="image3" alt="Diagram" /></td>
<td><img src="image4" alt="Diagram" /></td>
<td>Separates velocity into four sectors</td>
</tr>
<tr>
<td><img src="image5" alt="Diagram" /></td>
<td><img src="image6" alt="Diagram" /></td>
<td>Retains the total velocity and azimuthal direction</td>
</tr>
<tr>
<td><img src="image7" alt="Diagram" /></td>
<td><img src="image8" alt="Diagram" /></td>
<td>Retains component velocity and angular direction</td>
</tr>
</tbody>
</table>

Figure B-1
\[ \hat{r} = \hat{b} \times \hat{n}, \quad \text{Eqn B-7} \]

where \( \hat{B} \) is the magnetic field vector and \( \hat{V}_r \) is the plasma ram vector. Thus to determine the \( \text{nrb} \) system, the magnetic field and ram vectors must be expressed in a similar coordinate system. Because the magnetic field (from the onboard magnetometer) and the detected particle velocities are in initially in the local rocket frame of reference (pitch angle system discussed in section I-B), the rocket velocity needed to also be expressed in this system.

35.017's trajectory and in flight velocity were provided from the radar facility at the Poker Flats launch range. Both of these data were given in one second intervals with the trajectory given in Latitude, Longitude, and Altitude, while the velocity was in terms of a local spherical coordinate system. These velocities were transformed into a stationary Geocentric reference frame using the trajectory and a standard spherical to cartesian coordinate transformation. This was subsequently transformed into the local rocket reference using the aspect (yaw, pitch and roll of the rocket), which had previously been calculated by Hank Dolben, and the usual Eularian rotation transformation matrix.

When the needed vectors are all in a common coordinate system, the transformation matrix from the pitch angle coordinate system to the \( \text{nrb} \) coordinate system (\( u' = Au \)) can be calculated. If the unit vectors of the \( \text{nrb} \) coordinate system are expressed in the pitch angle coordinate system such that they are of the form:

\[ \hat{b} = b_1 \hat{e}_x + b_2 \hat{e}_y + b_3 \hat{e}_z \quad \text{Eqn B-8} \]
\[ \hat{n} = n_1 \hat{e}_x + n_2 \hat{e}_y + n_3 \hat{e}_z \quad \text{Eqn B-9} \]
\[ \hat{r} = r_1 \hat{e}_x + r_2 \hat{e}_y + r_3 \hat{e}_z \]. \quad \text{Eqn B-10} \]

then the transformation matrix is defined as:

\[
A = \begin{pmatrix}
  n_1 & n_2 & n_3 \\
  r_1 & r_2 & r_3 \\
  b_1 & b_2 & b_3 
\end{pmatrix}.
\] 

\quad \text{Eqn B-11}
Once the detected particle velocities can be transformed into the nrb coordinate system, the question then returns to which method should the distribution function be displayed.

The survey data presented in figures 1-19 and 1-20 were presented in the rocket frame of reference (no modifications to the detected velocity vectors) and used two folding techniques to illustrate the data. In the plots which contain the r and b axis a partial cylindrical fold was used to average the data (figure B-1b). In this method the data is expressed in cylindrical coordinates and divided into four equal sectors. The sectors are then azimuthally collapsed unto their respective axis. A polar fold (figure B-1c) was used for the azimuthal plane (n-r plane) presentation of the summary data. In order to avoid averaging in the ultraviolet contamination and the downflowing ions, the data in these plots were limited to polar angles less than 60 degrees from the n-r plane. These two folding processes retain the total velocity information and are quite good approaches for a summary plot. However, both processes also have their own drawbacks; the sector cylindrical fold requires at least six energy sweeps of data to have reasonable phase space coverage and as the size of the polar angle decreases it too tends to needs larger accumulation periods for complete azimuthal coverage. As the data was increasingly studied, a few modifications were made.

In order to best understand the distribution function plots, the frame of reference in which they are presented must be understood. In the case of a rocket flight the plasma being detected is modified by two experimental factors, the speed of the rocket and the potential to which the payload is charged. A lengthy discussion of this is presented by Morgan [1976] in which he shows how the thermal plasma flux will be more readily detected when it is being rammed into the detector as opposed to the opposite case when the detector is being sped away from the plasma at velocities greater than the thermal speed of the ions. Also because the electrons in the aurora are more mobile than the ions they will cause the payload to become negatively charged. This potential is felt by the ions when they are within one Debye length of the charged payload and cause the ions to be accelerated into the detector. Rocket payloads in the aurora typically charge to at least one volt. This means that thermal ions would then be detected at roughly one electron volt. The rocket potential may then be estimate by the first step on which an ion electrostatic analyzer first sees the thermal population. It must be noted that drift velocities also can cause a positive energy shift in the particle distribution. However, unlike the shift due to
TOPAZ 2
Rocket Potential

Figure B-2
rocket charge, the drift velocity is directionally dependent and can be distinguished from a potential shift. For flight 35.017 the first step at which there was a signal above the normal background noise in the HEEPS Total Counts in the HEEPS Low instrument was recorded as an estimated potential. This is shown in figure B-2.

Thus to display the distribution function in a stationary frame of reference, the detected particle velocity must be modified by subtracting the rocket velocity and velocity due to the rocket potential. In general the value of the distribution function is calculated from the detected energy values. This value can then be transformed into the stationary frame of reference because Liouville's theorem (see Appendix G of Morgan [1976]) states that the distribution function is conserved along particle trajectory when the mechanism acting upon the particles is of the Lorentz force type.

With these modifications made the data was then ready for display in a stationary frame of reference. For the evaluation of a single energy sweep of data the need to identify the actual (not projected) values of the distribution function's velocity coordinates is of the utmost priority. Thus for the phase space plot of the transversely accelerated ions, a projection collapse was used (figure B-1d). By examining the two projections, all three velocity components can be determined. The program used to calculate the distribution function had variable input parameters which allowed for the choosing of the size and location of the data that was to be averaged together. This made for the most comprehensive presentation of the data that was possible.
Appendix C

Determination of ExB Drift Velocity
From Ion Measurements

In an idealized ionosphere the motion of the charged particles can be described by the equation:

\[
\frac{dv}{dt} = \frac{q}{m} (v \times B) + \frac{F}{m},
\]

Eqn C-1

where \( v \) is the velocity of the particle, \( B \) is the geomagnetic field, and \( F \) is any additional constant force. Separating this into the components with respect to motion perpendicular and parallel to the geomagnetic field yields:

\[
\frac{dv_\perp}{dt} = \frac{q}{m} (v_\perp \times B) + \frac{F_\perp}{m},
\]

Eqn C-2

and

\[
\frac{dv_\parallel}{dt} = \frac{F_\parallel}{m}.
\]

Eqn C-3

Thus according to these equations of motion the particle will be accelerated along the magnetic field and perpendicular to magnetic field in addition to its gyromotion. To understand the perpendicular drift velocity due to this acceleration, the total perpendicular velocity of the particle can be written as:

\[
v_\perp = u + v_d,
\]

Eqn C-4
where $\mathbf{u}$ is the particle gyromotion velocity and $v_d$ is the constant perpendicular drift motion. Substituting this into equation C-2 and recalling that $dv_d/dt = 0$ (because $\mathbf{F}$ is constant) yields:

$$\frac{du}{dt} = \frac{q}{m} (v_d \times \mathbf{B}) + \frac{q}{m} (\mathbf{u} \times \mathbf{B}) + \frac{F_\perp}{m}. \quad \text{Eqn C-5}$$

If a coordinate transformation is made such that the new coordinate system is moving at the drift speed $v_d$, then the particle motion in this transformed coordinate system will be

$$\frac{du}{dt} = \frac{q}{m} (v_d \times \mathbf{B}) \quad \text{Eqn C-6}$$

In order for $v_d$ to satisfy equation C-5,

$$q (v_d \times \mathbf{B}) + F_\perp = 0. \quad \text{Eqn C-7}$$

must hold true. To solve for the drift velocity, the cross product of $\mathbf{B}$ and equation C-7 is taken and a vector identity can then be used to show that

$$v_d = \frac{1}{q} \frac{(F_\perp \times \mathbf{B})}{B^2}. \quad \text{Eqn C-8}$$

In the case of flight 35.017 perpendicular electric fields were measured which would cause a perpendicular force $F_\perp = qE_\perp$. In turn this force will induce a perpendicular drift velocity in the particles of:

$$v_d = \frac{(E_\perp \times \mathbf{B})}{B^2}. \quad \text{Eqn C-9}$$

The measurement of this drift velocity is well documented (e.g. Evans 1977) and has often been used to determine electric field strength and direction (Zanetti 1978). Therefore in terms of the parameters discussed in Appendix B, an ion phase space distribution displayed
in a stationary coordinate system (rocket motion and charge effects taken out) should show
an offset from the origin of the ion population due to this drift velocity. Figure C-1 shows
the electric field data taken by Cornell’s Weitzman boom aboard flight 35.017. The top
panel of figure C-1 shows the direction of the electric field in geomagnetic coordinates and
the bottom panel shows the magnitude of the electric field. The electric field is seen to be
below 100 mV/m and in the southeastern direction during the early portion of the flight.
Upon entering the high energy electron precipitation arc at ~480 seconds FT, the magnitude
of the electric field is seen to vary greatly reaching values as high as 450 mV/m. The
direction of the electric field is seen to change upon entering the arc to the mostly northern
direction and remains in that direction while in this arc. As the payload exited the arc the
magnitude of the electric field dropped to below 25 mV/m until entry of the second arc of
high energy electron precipitation at 700 seconds FT. The electric field is seen to behave in
a similar manner at this time as in the previous arc. An expanded view of the electric field
activity during the time period of 500-600 seconds FT is given in figure C-2.

Because the magnitude and direction of the geomagnetic field can be considered
constant for the time period shown in figure C-2, this figure also serves as a guide to the
expected drift velocity produced by the electric field. The direction of the drift velocity
\( \mathbf{V}_{E \times B} \) is perpendicular to both the magnetic and electric fields and therefore would be in
approximately the western direction during the time shown. The electric field magnitudes
of 250 mV/m and 500 mV/m correspond to drift velocities of 5 km/s and 10 km/s
respectively. Thus with the rocket velocity being approximately 2 km/s, a drift velocity of
this magnitude should easily be seen in phase space distribution of the perpendicular plane.
Figure C-3 shows four such plots during the period 500-600 seconds FT. These plots are
of the n-r plane (see Appendix B for details) with the estimated potential taken out but the
rocket velocity is not taken out. The orientation of the plots with respect to the
perpendicular geomagnetic plane is that the top center is north and the right center is east.
Therefore in the absence of an electric field the distribution is expected to be offset from the
origin by the ram velocity. The poor coverage of the perpendicular velocity space is due
to the syncing of the instrument energy sweep and the payload spin period (a 3 to 2 ratio).
Each plot’s start time is indicated above the plot and the data was accumulated for 12
energy sweeps (~10 seconds). These periods were chosen because they were times when
TOPAZ 2
Electric Field

![Graph showing electric field magnitude (mV/m) over flight time (sec)].

Figure C-2
steep fluctuations were not observed in the electric field data. Figure C-3a gives the data starting at ~525 seconds FT. During this time period the electric field data is seen to drop to below 50 mV/m (and therefore $V_{\text{ExB}}$ to less than 0.5 km/s). The ion data shows that the distribution has simply been shifted to approximately 3 km/s on the r-axis due to the ram velocity. This is consistent with the electric field data.

Figure C-3b started at ~547.5 seconds FT during times when the electric field data is seen to vary between 175 and 250 mV/m. This would imply a drift velocity of between 3.5 and 5 km/s. Because the drift velocity is comparable to the ram velocity, it is expected that the ion distribution for this data to be found in the southwest quadrant. However there is only a slight increase of flux in the southeastern quadrant and no noticeable increase in the southwest quadrant. The coverage in the southwest quadrant for this time period is poor and there is the possibility the flux peak was not detected during this time.

Figure C-3c is data taken from ~568 seconds FT while the electric field data reaches a value of 375 mV/m. This electric field magnitude would cause a drift velocity of 7 km/s which should be easily seen in the ion data. The plot shows that the southwestern quadrant was well covered during this time but that no increase in flux is seen there. Instead the location of the ion distribution is found to be 3 km/s from the origin on the r-axis. This is similar to the result found in C-3a.

The last data comes from ~584 seconds FT. This time presents the most stable large value of the electric field. The field is seen to plateau at a value of approximately 200 mV/m. Because a drift velocity of 4 km/s is expected from this value and it is comparable to the ram speed, the ion distribution should be shifted to the southwest quadrant. Inspection of the plot reveals a case very similar to the previous time period. The coverage of the southwest quadrant is more than adequate but the ion peak is seen to be simply shifted by the ram velocity.

Thus the ion data and the dual probe electric field data are in conflict for the times that the dual probe experiment indicates there is a large electric field present. It should be noted that the times of large electric field measurements coincided with the times of intense high energy electron precipitation. It was shown in Appendix B that during these times the payload was found to have charge up to as high as -7V. It must also be pointed out that the data from the dual probes was sinusoidal in nature thus giving the impression that it was
TOPAZ 2
Phase Space Distribution
Log(s^3/m^6)

a) Start Time 525.43

b) Start Time 547.55
TOPAZ 2
Phase Space Distribution
\[ \log(s^3/m^6) \]

c) Start Time 567.82

d) Start Time 584.41

Figure C-3
believable. At the present time the Cornell team is checking their common mode rejection process to try and determine if there was any error in the reduction of this data. However at this point in time it is firmly stated that the large flow velocities expected from the observed electric fields are not seen in the thermal ion detectors.
Appendix D

Plasma Wake

During the down leg portion of the flight an anomalous particle population was seen. Figure D-1 shows the sampling position of the HEEPS LO instrument for a period of 5 energy steps (~ 0.144 sec) during three consecutive energy sweeps (thick line on circle perimeter). The view given is in the pitch angle coordinate system (figure 1-14) and is viewing the payload from the front looking aft. Recall that the energy sweep and spin period were synced at an approximate ratio of 3 to 2 causing the HEEPS to return to the same azimuthal position every three energy sweeps. Figure D-1 also indicates the blind side of the HEEPS by the thicker line on the HEEPS instrument. As has been described in the previous portions on the HEEPS instrument, the HEEPS has three blind spots. The largest of these blind spots is approximately 30° wide. The HEEPS were mounted such that this large blind spot would not affect the viewing of upflowing or downflowing particles. Therefore the large blindspot was mounted perpendicular to the spin axis. Also shown on figure D-1 is the projection of rammed plasma assuming there are no large bulk drift flows. A well defined cold rammed plasma was observed during the times when the HEEPS instrument was in the position indicated for the n=1 energy sweep (recall this is during the downleg of the flight, therefore the plasma is flowing up as well as straight at the HEEPS). Cold rammed plasma was also seen on the edges of the large blind spot during the n=2 energy sweep. However an additional population was observed by the anti-ram looking bins during this time. Analysis of the energy required by those particles to be detected in these bins indicate that the energy is much higher then thermal energies. In addition the particles detected during energy sweep n=3 have a rammed plasma like signature but can not be numerically fit to a Maxwellian distribution. For these reasons it was proposed that perhaps the HEEPS was viewing some sort of wake effect. The following parts of this appendix give a review of plasma wake, some results of other reports of plasma wake effects observed during sounding rocket flights, an in depth
Projected Plasma Flow

Figure D-1
presentation of the wake data from the HEEPS instrument, and arguments why this data can be interpreted in this manner.

**Plasma Wake Review**

Wakes in plasma have been studied both theoretically and experimentally since the mid-1960's (Al'pert et al [1965], Kasha [1969]). The plasma Mach number, relative to the ion-acoustic wave speed, is given by the equation:

\[
M = V \left[ \frac{kT_e}{m_i} \left( 1 + \frac{3T_i}{T_e} \right) \right]^{1/2}
\]

where \( m \) is the ion mass, \( V \) is the object velocity, \( T_e \) is the electron temperature, and \( T_i \) is the ion temperature. For supersonic plasma flow speeds (\( M > 1 \)), the region immediately following an object is nearly empty of ions causing a boundary density gradient [Fourner and Pigache 1975]. The large thermal speed of electrons allow them to initially freely enter this space. Thus this region, called the near wake, will have a space charge set up in it. A schematic of the wake, taken from Fourner and Pigache [1975], is shown in figure D-2. In terms of a rocket payload, figure D-2 is similar to figure D-1 in that the drawing is in the rocket frame of reference viewing from the top looking aft. The z-axis is referred to as the centerline while the r-axis is simply called the transverse coordinate. Following the formation of the wake the ions try to fill the wake via three separate processes. The first process is the acceleration of the ions towards the centerline due to the space charge in the near wake. An ion density peak builds up at the region marked the mid wake in figure D-2 due to the meeting of ions from different parts of the wake edge. A wave-like disturbance travels from this density peak at the Mach angle \( \theta_M = \sin^{-1}(1/M) \) into a region known as the far wake. A second mechanism for filling the wake with ions is the charge of the body causing the wake. Ions which pass close to the body will be deflected towards the centerline and form a second density peak in the mid wake and a maximum deflection angle \( \theta_D \). The last mechanism for filling the wake is the thermal motion of the ions. This action will tend to negate the first mechanism described.

The characteristics of a wake is determined by several parameters. These parameters are: the ratio \( R/\lambda_D \), where \( R \) is the radius of the body forming the wake and \( \lambda_D \) is the
Plasma Wake Structure

Figure D-2
plasma Debye length; the dimensionless potential $\varphi = e\phi/kT_e$, where $\phi$ is the potential of the body and $kT_e$ is the electron temperature; the ratio of the electron temperature to the ion temperature $T_e/T_i$; and the Mach number given in equation D-1. For the case of flight 35.017, the parameters for the wake can be taken as $R/\lambda_D \gg 1$ and $T_e/T_i = 1$. Unfortunately no experimental laboratory work or computer simulation have been done in this realm. However there have been some reports of wake observations during sounding rocket flights. These results are discussed next.

Wake Phenomena Observed by Sounding Rockets

Effects of a wake on plasma observations during sounding rocket flights have been reported [Svenes et al. 1990a, Svenes et al. 1990b, and Bering 1983]. Svenes et al. [1990a] have reported the results found from the MAIMIK sounding rocket flight. Three plasma probes and an electric field dual probe were used to detect wake effects. The three plasma probes consisted of the electron temperature probe (ETP), the ion probe (IP), and the capacitance probe (CAP). The ETP is a spherical grid of 5 cm surrounding a collector biased +10 V relative to the payload ground. The ETP grid is swept from -2.0 to +3.0 V relative to the payload ground. The slope of the electron current yields the ambient electron temperature while the individual current measurement is proportional to the electron density. The IP worked in the same basic mode but was biased accordingly for ions. The CAP measured the capacitance of the sphere versus the surrounding plasma. The authors argue that this measurement is simply the square root of the ratio of the electron density to the electron temperature. The sampling rates of these instruments were much higher than the spin rate of the payload therefore giving a good azimuthal view of the plasma surrounding the rocket. Svenes et al. [1990a] observed that throughout the flight the electron and ion densities were depleted in the anti-ram direction (direction anti-parallel to the velocity vector). The electron temperature in this region was also found to be enhanced.

During the POLEWARD LEAP rocket flight Svenes et al. [1990b] reported additional observed wake effects. Using an ETP similar to that described above and a pair of suprathermal particle spectrometers, Svenes et al. [1990b] were able to make measurements comparable to that seen aboard MAIMIK. The authors report a positive correlation
between enhancements of the ambient electron temperature, depletions of the ambient electron density, and the position of the wake region. Svenes et al. [1990b] also reported the existence of suprathermal electrons in the wake region during the downleg portion of the flight. Lastly, the authors reported the slight shifting of the wake region from the anti-ram direction. This was attributed to the presence of a background electric field which would set up a plasma drift.

**Wake Observations by NASA Flight 35.017**

An example of the wake data from flight 35.017 is given in figure D-3. Pictured in figure D-3 is data from HEEPS Low (HL) for six consecutive image accumulation (energy step) periods with the flight time marked in the upper left hand corner. Each set of data contains the HEEPS Total Counts (HTC), as a solid line across the data, the pitch angle look direction (solid "sine wave"), the azimuthal look direction (squares), and the HEEPS Image for the accumulation bins listed on the horizontal axis. The data shown is from the downleg portion of the flight (~775 sec FT). Marked on the panels are the cold rammed ions and the ions from the direction anti-parallel to ram (here on referred to as the wake ions). These populations are identified from the pitch angle and azimuthal look angle. Ram particles detected on the downleg should be at 0° azimuth and >90° pitch angle. The only accumulation bins which have this criteria are at bin number = 0. An enhancement of ions is seen there and has been marked as ram particles. The wake ions are seen to have a pitch angle range of $30^\circ < \alpha < 100^\circ$. More important is the fact that these ions are detected at an azimuth of ~ 150° which corresponds to entering from slightly off of the anti-ram direction ($0^\circ$ azimuth is ram direction, $180^\circ$ azimuth is anti-ram direction). The contamination from the intense ultraviolet emission from the aurora is also marked in the first and last panels.

To better understand in which direction the wake ions are traveling when they were detected, a particle tracer was inserted into an analysis program. The results are shown in figure D-4 where the plot on the left is the azimuthal n-r plane and the right plot is the r-b plane where the magnetic field is the vertical axis. The data is taken over six energy sweeps which includes the data from figure D-3. The wake ions from the panel at time 774.75 in figure D-3 were coded such that they turn up as black in the plots in figure D-4. This clearly shows what was stated in the previous paragraph. The wake ions have
Figure D-3
TOPAZ 2
Phase Space Distribution
Log($s^3/m^6$)

Start Time 772.42

figure D-4
velocities ranging from positive to slightly negative in the parallel direction and negative in the ram perpendicular direction.

The wake ions were observed only on the downleg. Furthermore they were not observed while passing through the auroral structure of intense high energy electron precipitation (~720-760 secs FT) on the downleg. In reference to figure D-1, the data shown in figures D-3 and D-4 were from times when the HEEPS instrument was at an azimuth comparable to the n=2 energy sweep.

**Wake Ion Trajectories**

It was found by examining the velocities which were required for these ions to enter the HEEPS instrument that the wake ions must have energies greater than a thermal ion. It was proposed that perhaps a mechanism in the wake was causing thermal ions to experience an energy gain. For this to be true, it must be shown that the wake ions originated at some point in the wake and that any non-wake ions must not have originated from the wake. In the absence of a strong electric field, this is easily seen by calculating the trajectories of the ions in a magnetic field where the equation of motions perpendicular to the magnetic field are:

\[
\dot{x} = \Omega \dot{y} \quad \text{Eqn D-2}
\]

and

\[
\dot{y} = -\Omega \dot{x} \quad \text{Eqn D-3}
\]

where the dot refers to differentiation with respect to time and \( \Omega \) is the ion gyrofrequency. Solving these two for the appropriate initial conditions yields:

\[
x(t) = x_0 + \frac{v_\perp}{\Omega} \left(1 - \cos \Omega t\right) \quad \text{Eqn D-4}
\]

and

\[
y(t) = y_0 + \frac{v_\perp}{\Omega} \sin \Omega t \quad \text{Eqn D-5}
\]

where \( y_0 \) and \( x_0 \) are the initial position of the ion in the perpendicular plane and \( v_\perp \) is the
initial perpendicular velocity. The equation of motion for parallel to the magnetic field is simply:

\[ z(t) = z_0 + v_{||} t, \quad \text{Eqn D-6} \]

where \( z_0 \) is the initial position along the magnetic field and \( v_{||} \) is the initial parallel velocity.

Thus the quantities needed for the calculation described above can be found from the velocity magnitude and direction of the detected particles (\( v_\perp \) and \( v_{||} \)) and the position of the HEEPS instrument (\( x_0, y_0 \) and \( z_0 \)). To satisfy the criteria that wake particles originating in the wake region, a routine was established where single particle trajectories were calculated for the particles which could have (or were) been detected by a discrete number of accumulation bins. These bins were chosen such that they were representative of the whole strip and such that two of these bins were at the ends of the wake ions distributions (i.e. where in bin space the wake ions were detected). It should also be pointed out that these trajectories were for single energy steps. The results of the calculation of the trajectories for the energy step at time 774.75 (from the data presented in figure D-3) are shown in figures D-5 to D-9. The coordinate system in which the ion trajectories are presented has its axis such that the \( s \)-axis is the spin axis of the payload, the \( r \)-axis is the projection rocket velocity into the azimuthal spin plane, and the \( n \)-axis is perpendicular to the previous two axis (similar to the nrb coordinate system but using the spin axis instead of the magnetic field). The figures are arranged such that the plots on the left are projections in the \( r-n \) plane and the plots on the right are projections in the \( r-s \) plane. The + represents the location of the top of the payload and the dots represent the position of the ion. The trajectories start at approximately the origin (the origin is the center of the payload, ions start at position of the HEEPS) and have been mapped backwards in time for 30 milliseconds at 1 millisecond intervals. The accumulation bin number is marked at the top of the plots.

In order for the ion to be considered to originate from the wake in these plots, it must at some time have its marker behind the corresponding rocket marker in both projection planes. Figures D-5 and D-6 show the trajectories for particles from accumulation bins 3 and 12. Neither of these ion trajectories pass behind the rocket path and it is also clear to
TOPAZ 2
Ion Trajectories
Start Time 772.42

Bin = 3

figure D-5
TOPAZ 2
Ion Trajectories
Start Time 772.42

Bin = 12

figure D-6
TOPAZ 2
Ion Trajectories
Start Time 772.42

Bin = 26

figure D-7
TOPAZ 2
Ion Trajectories
Start Time 772.42

Bin = 42

figure D-8
TOPAZ 2
Ion Trajectories
Start Time 772.42

Bin = 60

figure D-9
see how the ions in bin 3 are being rammed into the detector. Figures D-7 and D-8 show the trajectories from accumulation bins 26 and 42 which correspond to the edges of the ion wake distribution (see figure D-3). Remember that the + symbol represents the top of the payload and that with the retention of the third stage motor, the entire payload extends approximately 4.5 meters down from the plus symbol. Also the wake is an extended region defined by the deflection angle $\theta_D$ and therefore the ions need not be directly behind the rocket path. Therefore the trajectories for these bins can be seen to be in the wake region for the second and third time steps before detection. Finally figure D-9 shows the trajectory for accumulation bin 60. It is again clear that this trajectory did not pass behind the rocket path. While the ion trajectories presented are from a single energy step, they are typical of the trajectories calculated during observations of wake ions.

Modified Maxwellian Numerical Fit

The initial contact with the wake ion data was an attempt to numerically fit the data with a Maxwellian described in equation 1-32. This time late in the flight and out of an auroral structure was thought to be an ideal counterpart to the cold rammed plasma observed and numerically fitted on the upleg (figure 1-24). An example of an attempted Maxwellian fit of the observed data presented in figure D-3 is given in figure D-10a. The parameters used were: $n = 1000 \text{ cm}^{-3}$, $U = 1.45 \text{ V}$, $kT = 0.098 \text{ eV}$, and $V = 0 \text{ km/s}$. The ram peak is in agreement in both figures with the data from the HEEPS being narrower in bin space. This is probably due to the poor response of the accumulation bins near zero. However a comparison of Maxwellian fit in figure D-10a to the data in figure D-3 does reveal differences. The Maxwellian fit in figure D-10a has no trace of any of the wake ions marked in figure D-3. This is the case for all of the Maxwellian fits of the wake ion data. This inability to numerically fit the data and the knowledge that the wake ions that were observed had to have energies larger ($\sim 1.0 \text{ eV}$) than thermal energies ($\sim 0.1 \text{ eV}$) led to the hypothesis that these wake ions were simply thermal ions which had been accelerated by some mechanism in the wake. While it is beyond this thesis to describe this mechanism, it was assumed that the mechanism was of the Lorentz force type. Therefore the single particle distribution function is conserved along the particle's trajectory according to Liouville's theorem (e.g. see Morgan 1976). This enables the numerically generated
TOPAZ 2

a) Maxwellian Fit

b) Modified Maxwellian Fit
Maxwellian single particle distribution function to be modified such that a select part of the distribution could be accelerated by a desired amount. In numerical terms this can be expressed:

\[ f(v_i) \rightarrow f(v'_i), \quad \text{Eqn D-7} \]

where

\[ v'_i = v_i \hat{e}_i, \quad \text{where } i \text{ is not selected} \]

and

\[ v'_i = (v_i + u) \hat{e}_i, \quad \text{where } i \text{ is selected} \]

The results of the modified Maxwellian fit are given in figure D-10b and are for the same parameter as are listed above. The generated Maxwellian was modified such that the particles with velocity vectors in the direction of the wake accumulation bins from the energy step at time 774.75 received \(~1\, \text{eV}\) of acceleration in the direction of the chosen trajectories. This single modification was intact for the entire energy sweep. It is seen in figure D-8b that the wake ion distribution is reproduced in good agreement by this modification. The good agreement of the wake features for the energy steps past time 774.75 shows that this modification is valid. The spinning of the payload causes an ever changing velocity selection by the accumulation bins. Therefore if the modification was not correct a uncorrelated peak should be seen at some later energy step. Instead the velocity selection of the accumulation narrow the modified distribution in a similar manner as is seen in the wake ion data.

Conclusions

Results from observations of ions originating from the wake region behind a ionospheric sounding rocket flight have been reported. These ions have measured energies (~1eV) which are above thermal energies. The ion distributions have been numerically fit with a modified Maxwellian single particle distribution function where select portions of the distribution have been accelerated.
While these are rather preliminary results, the data from flight 35.017 has shown many new aspects of experimental acquisition of data via sounding rocket flights. The question of why this effect has not been previously observed in numerous sounding rocket flights can be answered. The geometry of the HEEPS instrument is very different than any previous flown ion detector. The acceptance plane of the HEEPS is transverse to deployed position (see figure D-1). A traditional particle detector looks in same direction as it is deployed. Thus in the case of the n=2 energy sweep in figure D-1, a traditional particle detector would look away from the wake region while the HEEPS instrument is looking into the wake region. For this reason it is possible to obtain new results. However because this phenomena was not anticipated during the design review of the Topaz rocket, the data presented can not give a full view of the science of the mechanisms involved. However the wake phenomena could easily be studied with a set of four HEEPS mounted ninety degrees apart on a slow spinning high velocity rocket in the ionosphere. With this simple configuration the evolution of the ion distribution in the azimuthal plane would be evident.
REFERENCES


