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ELECTRODYNAMICS OF AN ION INVERTED V

Rice University

Ph.D. 1984

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ELECTRODYNAMICS OF AN ION INVERTED V

by

GEORGETTE OLIVE BURGESS

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

DOCTOR OF PHILOSOPHY

APPROVED, THESIS COMMITTEE

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Houston, Texas
August, 1983
"You are sad," the Knight said in an anxious tone: "let me sing you a song to comfort you."

"Is it very long?" Alice asked, for she had heard a good deal of poetry that day.

"It's long," said the Knight, "but it's very, very beautiful. Everybody that heard me sing it—either it brings the tears into their eyes, or else..."

"Or else what?" said Alice, for the Knight had made a sudden pause.

"Or else it doesn't, you know. The name of the song is called 'Haddocks' Eyes.'"

"Oh, that's the name of the song, is it?" Alice said trying to feel interested.

"No, you don't understand," the Knight said, looking a little vexed. "That's what the name is called. The name really is 'The Aged Aged Man.'"

"Then I ought to have said 'That's what the song is called?'" Alice corrected herself.

"No, you oughtn't; that's quite another thing! The song is called 'Ways and Means': but that's only what it's called, you know!"

"Well, what is the song, then?" said Alice, who was by this time completely bewildered.

"I was coming to that," the Knight said. "The song really is 'A-sitting On A Gate': and the tune's my own invention."

Through the Looking Glass
Lewis Carroll
ELECTRODYNAMICS OF AN ION INVERTED V

by

Georgette Olive Burgess

ABSTRACT

Particle precipitation around the earth's polar regions may be the footprint of various energizing phenomena in the magnetosphere. Satellite-observed electron fluxes whose peak energy increases then decreases are called inverted V's.

The Atmosphere Explorer-D Low Energy Electron (LEE) data for January 11, 1976 indicates that the precipitating ions have been accelerated. In this event the spectrogram of the ion flux shows the change of the peak energy with time characteristic of an inverted V. The electron population is decelerated as the ion population is accelerated, consistent with a downward electric field.

The Birkeland current at an inverted V may be calculated in two ways: from the divergence of the electric field or from the observed particle fluxes. We found that the two methods agree on the location of Birkeland current throughout the event, but the magnitudes are not the same. This is not surprising, since the component of \( \nabla (\mathbf{E} \cdot \mathbf{n}) \) perpendicular to the trajectory can not be determined.

The electric potential along the spacecraft's trajectory (790-650 km altitude) was calculated from the measured electric fields. The sum of the parallel potential drop (inferred from the ion distribution function) and the ionospheric potential gives the potential profile at the magnetosphere. The parallel electric field thus partially decoupled the
ionospheric flow from the magnetospheric flow.

The electric field pattern in the magnetosphere-ionosphere system demands field-aligned currents. When the thermal current is insufficient, a field-aligned potential drop can accelerate particles to satisfy the requirements. The thermal electron current from the ionosphere is much greater than that from the magnetosphere. Thus, it is more common to observe the signatures of an upward electric field: the electron "inverted V".

In the ion inverted V observed during AE-D orbit 1141, the postulated parallel potential has reduced the required parallel current. This high potential had to develop because the required amount of downward current would have quickly evacuated the ionospheric electrons available to supply the original requirement of downward current.
ACKNOWLEDGMENTS

My first thanks go to my thesis advisor, Dr. Patricia Reiff. I am grateful for her direction and her encouragement.

Next I wish to thank Drs. Richard Wolf and Tom Hill. Their teaching, comments on my research, and letters of recommendation were greatly appreciated. I wish to thank my academic great-grandfather, Dr. Alex Dessler. He has always retained an assortment of interesting projects and I have enjoyed participating in some of them. I am especially grateful for the opportunity to help with Physics of the Jovian Magnetosphere. Also, Drs. Stebbings, McLellan, Anderson, and Michel have helped me at various stages of graduate school.

Dr. Huey-Ching Yeh has been both a friend and a valued colleague. My special thanks go to Dr. Pat Lestrade, who has kept my amused.

I am extremely grateful to Jerry Mays for his help in typing my thesis.

This research has been partially supported by NASA grants NGR-44-006-137 and NSG-5286.

Finally, I dedicate this thesis to my mother Mrs. Olive Burgess, my first teacher. In a way, graduate school began when she taught me how to memorize all the bones of the body in one night.
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I. Introduction

Definition of an Inverted V

An inverted V event is a signature in the particle flux observed by a satellite-borne instrument. The name derives from the appearance of the energy-time spectrogram which presents the data. The spectrogram will be described fully in section III. For now, it is sufficient to note that the inverted V shows that at a given energy the particle flux peaks. During the event, the location of the peak moves up, then down in energy. On the spectrogram, this looks like an upside down V.

A spectrogram usually shows J, the differential particle flux. This is the number of particles per (area-steradian-sec-energy). The inverted V is most easily discussed in terms of the particle distribution function. Section IV describes this in detail. The distribution function, F, is the number of particles per unit phase space. (Since F ∝ J/E, the energy where the peak is located on the spectrogram differs from the energy at which the peak occurs in F.) F for a non-flowing Maxwellian distribution falls exponentially with particle energy, E, with a maximum at E = 0. This means that a plot of the log of F versus energy will be a straight line. During an inverted V event, however, this plot is no longer monotonic, with a secondary peak in F occurring at a certain energy, E_p. Throughout the inverted V, the peak moves up and then down in energy. The spectrogram plots look as though a normal Maxwellian distribution (with largest F at E = 0) had been accelerated by giving each particle an additional energy of E_p. This means that
particles which originally had zero energy now have an energy of $E_p$. Thus, the location of the largest value for $F$ now occurs at energy $E_p$, rather than zero. Sometimes secondary particles with energies below $E_p$ complicate the distribution. Their effect will be discussed in section V.

**Brief Description of the Relationship of Inverted V's to the Visual Aurora**

The accelerated particles observed in an inverted V are associated with the visual aurora (Meng, 1976). The two phenomena occur on different spatial scales, however. The width of an auroral form viewed visually from the ground may be as narrow as 100 meters (one football field). An inverted V region, on the other hand, must be at least a few tens of kilometers wide to be recognized in satellite measurements, although bursts may be seen at the lowest time resolution of the spacecraft (1/16 sec). For the Atmosphere Explorer D satellite (AE-D) this limit is about 25 km (0.2° latitude).

Aurora may also be observed from spacecraft, as the Defense Meteorological Satellite Program (DMSP) satellites as well as ISIS and Dynamics Explorer spacecraft, take pictures of the auroral oval, (Reiff, 1983a). These show light emissions over one or two degrees in latitude (100-200 km). Often more filamentary regions of emission are embedded in the wider-scale features or extend from them. These narrow features often correlate with enhanced particle precipitation, as seen by the particle detectors on DMSP. At present, observations suggest that
inverted V's are associated with the visual aurora, but ground observations show auroral features (arcs) with a scale smaller than the resolution of the satellite instruments which record the inverted V signature (Meng, 1976, 1981; Tanskanen et al., 1981; Lui et al., 1977; Swift, 1981; Reiff, 1983b).
II. Description of the Instruments

The Atmosphere Explorer Series

The Atmosphere Explorer series comprises three spacecraft: AE-C, AE-D, and AE-E (Dalgarno et al., 1973). Together these three made a coordinated exploration of the thermosphere, upper ionosphere, and lower magnetosphere. The thermosphere is the region of the upper atmosphere between 150 and 500 km. It derives its name from the high kinetic temperatures of its particles. AE-A and AE-B were more primitive and had been launched in the mid-60's. AE-C, AE-D, and AE-E were designed to study the chemistry of the thermosphere and its energy balance. At the lower limit of the thermosphere, the atmospheric drag causes a satellite's orbit to decay rapidly. Since at least a one year lifetime for a satellite was desired, the orbit was initially elliptical, dipping down to the lower thermosphere only at perigee. The satellites were constructed to endure a perigee as low as 120 km. Usually data were only acquired for the times around perigee, when the satellite was in the thermosphere. The ion inverted V, the topic of this thesis, was observed when the satellite was at 790-650 km altitude.

The Atmosphere Explorer-D satellite was in a nearly polar orbit, inclined 98° to the Earth's geographic equator. Figure 3.2 shows the path of the satellite (southern polar pass) for orbit 1141. The coordinates are invariant latitude and magnetic local time. As seen from any point on the Earth, AE-D moves geographically west. Since AE-D passes within 8° of the geographic poles, its ground track can pass in
between the geographic and magnetic poles. In that case AE-D appears to move toward the east in geomagnetic time (or longitude).

The LEE Particle Detector

The Low Energy Electron experiment (LEE) is an ion as well as electron spectrometer (Hoffman et al., 1973). AE-D carried 19 particle detectors, as opposed to AE-C's three detectors. Sixteen of these are fixed energy. The other three step in energy from 200 eV to 24.9 keV. One detects ions and the other two detect electrons at two pitch angles. When the spacecraft was in a spinning mode, the spin axis was normal to the orbital plane, so the detectors sampled a range of pitch angles. Although the spacecraft was spin stabilized, it contained a stabilizing inertial wheel so that it was possible to put AE-C or AE-D into a despun mode. In the despun mode it rotates once per orbital revolution. Much pitch angle resolution is then sacrificed for better energy resolution at a few pitch angles. To study the (ion) behavior in inverted V events, we wanted to contrast the acceleration or deceleration of the ions with the electrons. A simple model of electrostatic behavior predicts that acceleration for one must accompany deceleration for the other. Thus, detailed energy resolution was preferred to pitch angle information. Even so, we sampled two pitch angles, viewed by the two stepped energy electron detectors. They sampled pitch angles nearly parallel and at about 60° to the magnetic field. At a given second, the fluxes at the two different pitch angles were much more similar to each other than the fluxes at successive seconds, for a given pitch angle.
So to study electrostatic acceleration of electrons and ions, the despun mode is more useful.

The stepped energy detectors sample the particle flux in sixteen different energy windows each second. The energy steps are spaced logarithmically and the center energy of each ranges from 0.2 to 24.9 keV. This energy range was selected in order to measure the particles that generally provide the primary energy input into the upper atmosphere at high latitudes.

A LEE particle detector is composed of two basic instruments: a cylindrical electrostatic analyzer and a channeltron electron multiplier. The analyzer applies a series of voltages to electrostatic deflection plates for each detector, with higher voltages allowing successively higher energy particles to be detected. The stepped detectors cycle through the 16 center energies each second. Particles outside the desired energy range hit a wall before they reach the particle detection electronics. Figure 2.1 shows the limiting paths which just allow particles which have energies at either edge of the energy window to pass through the electrostatic analyzer. The total energy bandpass is about 31% of the center energy. The energy window extends from $E_c + 17\% (E_c)$ to $E_c - 14\% (E_c)$. The exact trajectory which a particle follows and the limits of the energy window depend on the direction in which the particle was traveling when it entered the electrostatic analyzer.

Most particles will be traveling nearly parallel to the plates, since they must have passed through a series of sunshade baffles before reaching the interplate region. Only particles with trajectories nearly parallel to the symmetry axis of the sunshade can reach the plate aper-
Particle Energy | 24.9 keV | 28.6 keV
Location in Energy Window | Center | Maximum
Entry Angle | 0° | 2°

Figure 2.1 The particle b with energy equal to the upper bound of the energy window would not have reached the counting apparatus at the far end if it had had a larger entry angle or had entered closer to the outer wall.
ture. The baffles shield the inner electronics from sunlight unless the sun is within 15° of the detector axis. This corresponds to a particle viewing acceptance angle of about 15° (Hoffman et al., 1973).

LEE cannot distinguish between any two ions which have the same energy/charge ratio. A 1 keV proton and a 2 keV He⁺⁺ ion cannot be distinguished, using only the LEE instrument. Using data from another instrument, the retarding potential analyzer or RPA, the general ionospheric composition may be determined. Since the ionic composition comes from curve-fitting RPA data and the curve parameters are sometimes difficult to determine, for any given second it is impossible to say with absolute certainty that 5% of the "protons" detected at a certain energy were not O⁺⁺ of double that energy. However, by comparing RPA curve fits at different times, one can build up an idea of the heavy ion composition during an event. However, it is certainly not necessary that the ionospheric composition (< 50 eV), measured by RPA, is the same as the more energetic ions (> 200 eV) measured by LEE. The RPA instrument will be described later.

The channeltron electron multipliers are the particle sensors. A particle which has the proper energy/charge ratio and charge sign will pass between the electrostatic analyzer plates without hitting any wall. It enters the channeltron where it initiates a cascade of electrons. The electron multipliers were operated in a pulse-saturated mode. Whenever a particle entered the channeltron, it caused a cascade which indicated that a particle had entered. The gain was turned so high that no energy information was provided by the pulse height of the cascade, so it could be used to distinguish among various energy/charge ratios. If
another magnetospheric particle entered the instrument during the cascade produced by an earlier particle, the second particle would not be counted. This effect produces a dead time in the LEE instrument. It is not a problem, however, unless the incident particle flux reaches 100,000 counts/second. In practice, this is seldom achieved for electrons and never for ions.

The data from the LEE instrument will be described in section 3.

This section has summarized information contained in an unpublished manuscript by Hoffman and Janetke (1977); a paper by Hoffman et al. (1973), and from Reiff (personal communication).

Instruments to Measure Velocities

The retarding potential analyzer (RPA) and the drift meter (DM) measure ion velocities. The drift meter measures velocity in a plane perpendicular to the spacecraft’s motion. The drift meter compares the ion current hitting different quadrants of an ion collection plate array. The relative motion of the ions and the spacecraft partially shields some sections of the array; those quadrants contribute less current. This is illustrated in Figure 2.2. The retarding potential analyzer measures velocity parallel to the spacecraft’s motion. An outward-directed electric field opposes the ions’ motion into the RPA. In order to overcome the applied potential $\phi_{\text{RPA}}$, an ion must have energy greater than $q\phi_{\text{RPA}}$, where q is the ion’s charge. The parallel velocity depends on both the charge and the mass of the ion. The next sections discuss the RPA and DM in more detail.
Figure 2.2 Particles entering the drift meter at angle $\alpha$ to the look-axis will cause a larger current ($I_2$) from the lower two quadrants than from the upper two quadrants. The lower two are partially shielded from the incident flux.
Figure 2.3 shows the coordinate system associated with ion velocities. It is centered on the spacecraft. The x-axis is defined as the look axis of the RPA. When the spacecraft is aligned in the despun mode, the y-axis points either toward or away from the Earth. For AE-D orbit 1141 the y-axis points up away from the Earth. The z-axis completes a right-hand coordinate system. When the spacecraft spins, \( \hat{z} \) is the spin axis. For our despun orbit, the \( \hat{x} - \hat{z} \) plane is the horizontal plane (tangent to the Earth).

The Drift Meter

Figure 2.2 illustrates the basic principle of the drift meter. For ions which have either \( v_y \) or \( v_z \) velocity components, part of the collector array is shadowed. Electrons are deflected away from the DM by a negative suppressor grid. If the ions moved exactly perpendicular to the sensor face, equal currents from the ion impacts would flow from each of the four quadrants. In this case the angle of attack is zero. Non-perpendicular velocities lead to unequal currents. For example, if the ions have a downward relative velocity, sections of the two upper quadrants are shadowed. The upper quadrants have a reduced effective area; this reduces the current flowing from the two upper quadrants, relative to that from the two lower quadrants. This gives \( v_y \), the vertical velocity component. The quadrants may be paired so that the current in the right half is compared to the current in the left half. This gives \( v_z \), the horizontal velocity component, which is also perpendicular to the spacecraft's motion.
Figure 2.3 Coordinate system used for velocities measured by DM and RPA.
The velocity from the drift meter, $v_y$ and $v_z$, depend only on ratios of current from two halves of the collector array (and the spacecraft velocity). They are insensitive to ion composition or to changes in the absolute ion concentration. Satellite attitude information limits their absolute accuracy relative to the Earth to about ±100 m/sec. For this event, the interesting velocities ranged from several hundred m/sec to over a km/sec. The telemetry sampling rate limits the spatial resolution to an average of 270 m. The drift meter is most sensitive for ion concentrations between five hundred and five million per cubic centimeter. For this event, the ion concentration was about $10^6$/cm$^3$, within the range for best sensitivity.

Information in this section was summarized from Hanson et al. (1973) and Hanson and Heelis (1975).

The Retarding Potential Analyzer

The retarding potential analyzer measures ion velocities in the direction of the spacecraft's motion. The RPA sensor looks directly along the spacecraft's velocity vector, so this component is called the ram velocity. A suppressor grid prevents electrons from entering the apparatus. Further inside, an outward-directed electric field of potential $\phi_{RPA}$ prevents an ion from entering the collection apparatus unless it has enough energy to overcome $\phi_{RPA}$. An ion can contribute to the current only if $(1/2)mv_y^2 > q\phi_{RPA}$. This means that the current from the RPA, for a given applied potential $\phi_{RPA}$, depends on the ion's ram velocity, mass, and charge. Figure 2.4 shows curves plotting current
Figure 2.4 (Adapted from Hanson et al., 1973)

Raising the retarding potential of the RPA shuts off the current from increasingly heavier ions. $M_n$ is the atomic mass of the ion $M_n^+$. 
against $\psi_{RPA}$. The actual curves depend on the ambient ion composition in a very complicated way. As $\psi_{RPA}$ is raised, different additional ionic components are turned away by the applied potential. The RPA team had developed computer routines which perform least square fits to these curves and produce self-consistent values for the ambient ion temperature and concentration, some ion composition information, the vehicle potential, and the ram velocity. After the known vehicle velocity has been subtracted, this gives $v_x$, the third component of the ambient ion velocity. The $v_x$ and $v_z$ components are the horizontal drift velocities for the ions.

Information in this section was summarized from Hanson et al. (1973), Hanson and Heelis (1975), and from Spiro (personal communication).

The ion drift velocities will be used to calculate electric fields and to infer the electric potential structure throughout this event.
III. Description of the Event

The inverted V signature is a familiar feature of electron energy-time spectrograms observed at high latitudes. Figure 3.1 shows a particle spectrogram. The x-axis shows the universal time (UT) of the observation. The y-axis is a logarithmic energy scale ranging from 200 electron volts (eV) to 30 kiloelectron volts (keV). The differential particle flux \( (J) \) is plotted as a grey scale in particles per (square centimeter-steradian-second-kiloelectron volt). This particular spectrogram will be described in more detail later.

On a particle spectrogram, an inverted V shows up as a broad dark line which slants upward, then back down. This means that the line is increasing and then decreasing in energy. It is darker than the surrounding areas of the plot because the particle flux peaks there. This looks like an upside down V on the spectrogram, so the phenomenon was named an inverted V. I will call an inverted V observed in the electron flux an electron inverted V.

Although inverted V's are observed in the polar cap, they are more common in the auroral oval, where field lines map to the boundary plasma sheet (Lin and Hoffman, 1979; Winningham et al., 1975). Electron inverted V's can occur at all magnetic local times (MLT) and on either open or closed field lines. They are most common in the dusk sector of the auroral oval. They are strongly associated with the region of auroral discrete arcs, but there can be electron inverted V's with no directly associated aurora visible from the ground or on satellite photographs (Meng, 1976; Tanskanen et al., 1980).
I will present data recorded by the Atmosphere Explorer D satellite. This is the first observation of an inverted V signature in the ion flux, although ion beams have been observed by the S3-3 satellite (Fennell et al., 1979).

Figure 3.1 shows electron and proton spectrograms. The fluxes were measured by the Low Energy Electron (LEE) detector. The LEE instrument was described in section 2. These are precipitating particles. The electrons are shown at two pitch angles: nearly field aligned (top) and at about 60° to the field line (middle). The bottom strip shows the ion flux at 60°. Since this event occurred in the southern hemisphere, a precipitating field-aligned particle has a pitch angle of 180° and the particles measured by the 60° detector have pitch angles of 120°. It is conventional, for the LEE instrument, to label the particles with the detector which observed them. So the protons will be called 60° particles.

The field-aligned and 60° electrons are nearly isotropic. The variation between the two pitch angles for a given second greatly exceeds the variation between successive seconds for the same pitch angle. The satellite carries only one stepped-energy ion detector, the 60° detector.

In Figure 3.1 the inverted V signature appears in the ion flux. I will call this an ion inverted V. The ion differential particle flux peaks at a given energy. The energy at which the peak flux is observed increases above the detector maximum of 28 keV and then decreases. There is also a minimum cutoff energy, below which virtually no ions are detected. This cutoff energy rises and then falls in the manner charac-
teristic of an inverted $V$.

As the cutoff energy becomes large, the flux of electrons is depressed. The cutoff energy rises in section 1. In sections 2.1, 2.2, and 2.3 (see Fig. 3.1) the proton cutoff energy in general decreases. There are also two smaller segments, within this general decrease, where the cutoff energy rises again. During these small inverted $V$'s, the electron fluxes are depressed, as they were for the main inverted $V$. Even on this small scale, the ion and electron fluxes anticorrelate. These are the first examples of one big and two small ion inverted $V$'s.

Figure 3.2 shows the location of the events in Magnetic Local Time (MLT) and Invariant Latitude (INVL or $\Lambda$). Area 1 corresponds to section 1 of Figure 3.1 and area 2 corresponds to sections 2.1, 2.2, and 2.3. In the blank area between 1 and 2, the peak energy apparently exceeded the detector maximum of 28 keV. The orientation of this figure is such that the angular momentum due to the rotation of the earth points into the paper (i.e., the figure shows the view from above the south magnetic pole). 18 MLT is dusk and 22 MLT approaches midnight. The south invariant magnetic pole is located at the origin of the radial hour lines.

Temporally, these events lasted nearly two minutes. They occurred in the early evening and extended over an hour of magnetic local time. Most auroral structures align themselves in the magnetic east-west direction. The satellite was probably flying along parallel to the structure, sampling it only gradually in the north-south profile over a three degree latitude range. The observations began at an invariant latitude of 72° and extended to nearly 75°. Lin and Hoffman (1979) per-
formed a statistical study of electron inverted V's. They found that the low latitude boundary of the occurrence region lies at about 62° for the 20-22 hour MLT region. They observed that the number of events became independent of MLT at latitudes higher than 80°. Thus, this ion inverted V at 72°-75° in the evening occurs in a region where inverted V's are commonly observed in the electron flux. Acceleration mechanisms often exist on field lines mapping to this area. In this case, it is the ions which are accelerated, rather than the electrons.

Lin and Hoffman found that the width in latitude for electron inverted V's was strongly peaked below 1/2°. They did observe events over 4° in width. So this ion inverted V, which is at least 3° in latitudinal width, is comparatively a broad structure. This will be relevant later in the section on acceleration mechanisms.

Because the satellite was moving nearly along a circle of invariant latitude, the extent of the event in MLT could be given a lower bound. Most of the orbits sample inverted V's mainly in latitude because the satellite is moving north-south. Consequently, Lin and Hoffmann found that electron inverted V's show a strong peak in longitudinal widths of less than one hour MLT. However, they have observed two events extending over nearly two hours of MLT (30° longitude). This means that the acceleration mechanisms operate continuously (in the mathematical sense) over a shell of field lines throughout a couple of hours of magnetic local time.

Lin and Hoffman found that the maximum peak energy for electron inverted V's was greatest for the evening hours. Average values for these MLT's range from 4-6 keV, but events with peak energies in the
20's of keV also occur. Since this ion inverted V peak energy exceeded
the detector maximum of 28 keV, it is on the energetic side. In the
section on acceleration mechanisms, we will see that this is suggestive.

The geomagnetic indices, DST and AE, are shown in Figure 3.3. The
ion inverted V was observed 3-4 hours after the DST indicated the maxi-
mum magnetic disturbance of a storm. The storm was abnormally intense.
This event occurred between two substorms, as indicated by AE. The pre-
ceding substorm which occurred between midnight and 0100 UT saturated
the AE graph at 2500 gammas. I have searched AE-D and AE-C data during
large storms, but failed to find another clear example of a candidate
ion inverted V.

In summary, this ion inverted V was broad in latitudinal and longi-
tudinal extent compared to electron inverted V's, but lay within the
extrema of the electron observations. It occurred in the same region
where many electron inverted V's are observed. It's peak energy was
comparatively high. The magnetosphere was very disturbed.
IV. Theory of Distribution Functions

The AE-D data base incorporated the option of presenting particle spectra in the form of the distribution function. The data are presented in graphs of log distribution function versus energy. In this format a Maxwellian distribution appears as a straight line, so long as the flow velocity $u < < w$, the thermal velocity.

In this section I will discuss the theory of distribution functions. There are several types of distribution functions, depending on the number of particles (1-particle to N-particle distribution functions) and the number of dimensions considered. I will place the experimentally determined distribution function in this context. The method of obtaining macroscopic plasma parameters (such as temperature) will be described in section 5. The equations describing the behavior of the distribution function are the Liouville equation and its descendants, the Boltzmann and Vlasov equations. I will relate the theoretical basis and evolution which supports the data analysis.

The fundamental physics which underlies this work is most elegantly stated in the Liouville equation. The most succinct version of the Liouville equation is $dF_N/dt = 0$, where $F_N$ is the N-particle distribution function. It is also true that $dF/dt = 0$ if there are no collisions (Krall and Trivelpiece, 1973) and if $\nabla_v \cdot F_s = 0$, where $F_s$ is an external force and

$$\nabla_v \cdot F_s = \frac{\partial}{\partial v_x} F_{s,x} + \frac{\partial}{\partial v_y} F_{s,y} + \frac{\partial}{\partial v_z} F_{s,z}$$
(Wolf, class-notes). This $F$ is any version of the distribution function and $d/dt$ is the total (convective) derivative in whatever dimensional phase space is appropriate for the $F$. If $F$ is an $N$-particle distribution function $F_N (x_1, x_2, \ldots, x_N, v_1, v_2, \ldots, v_N, t)$, it is the probability that particle $i$ will be found within $dx_i$ around $x_i$ with velocity within $dv_i$ around $v_i$ for all particles $i = 1$ to $N$. This distribution function has units of time$^3$/length$^6$ per particle. In order to plot the position of a particle in a manner which shows both its spatial location and its velocity, six coordinates must be specified in a six-dimensional phase space. Since $F$ is a function of these same six coordinates it could also, for a given time, be plotted on the same six-dimensional graph. In addition, $F$ also depends on time. Liouville's Theorem does not mean that if there are no collisions and $\vec{v} \cdot \vec{F}_s = 0$, the plot of $F$ in this six-dimensional space is constant. It does mean that as a particle moves through this six-dimensional space, the value of $F$ at the particle's location (wherever that is in the six dimensions) is constant.

In this thesis the data are analyzed using a single particle three-dimensional distribution function.

The distribution function for a non-flowing Maxwellian is

$$F = n \left[\frac{m}{2\pi kT}\right]^{3/2} \exp \left[-E/kT\right].$$  \hspace{1cm} (4.1)

$F$ is a three-dimensional distribution function and has units of sec$^3$/m$^6$, $n$ is particle density in number of particles/cm$^3$, $E$ is particle energy in keV, and $(3/2) kT$ is thermal energy of particles (assuming three
degrees of freedom) in keV). This may be rewritten as:

\[ F = C_{\text{BE}} n \left(\frac{1}{kT}\right)^{3/2} \exp \left[-\frac{E}{kT}\right] \]  \hspace{1cm} (4.2)

where \( C_{\text{BE}} = 2.72 \times 10^{-17} \) for electrons, with units as listed above, and equals \( 2.14 \times 10^{-12} \) for protons.

Since \( F \) depends on energy exponentially, plots of \( \log F \) versus \( E \) are straight lines. Later, I will demonstrate that this dependence satisfies the collisionless Boltzmann equation.

Consider an accelerated species of charge \( q \) and a decelerated species of charge \( -q \). The external force corresponds to a potential \( \phi \).

For the accelerated species,

\[ F = n_0 \left(\frac{m}{2\pi kT}\right)^{3/2} \exp \left[\frac{-E + q\phi}{kT}\right] = F_{\text{before}} \cdot \exp \left[\frac{q\phi}{kT}\right]. \]  \hspace{1cm} (4.3)

For the decelerated species,

\[ F = n_0 \left[\frac{m}{2\pi kT}\right]^{3/2} \exp \left[\frac{-E - q\phi}{kT}\right] = F_{\text{before}} \cdot \exp \left[-\frac{q\phi}{kT}\right] \]  \hspace{1cm} (4.4)

\( n_0 \) is the source particle density, i.e., measured before the particles encountered the potential \( \phi \) and were accelerated or decelerated.

I will now demonstrate that this form of the distribution function satisfies the Boltzmann equation.

Boltzmann equation:

\[ \frac{\partial F}{\partial t} + \vec{v} \cdot \nabla F + \left( \frac{F}{m} \cdot \nabla \right) F = \left( \frac{\partial F}{\partial t} \right)_{\text{collisions}} \]
Where $F$ is the electromagnetic force. Approximate $(\partial F/\partial t)_c = 0$. The Boltzmann equation then becomes the (collisionless) Vlasov equation.

$$\frac{\partial F}{\partial t} + \sum_{i=1}^{3} \left[ v_i \frac{\partial F}{\partial x_i} + \frac{e}{m} \left( E_i + (\nabla \times B_i) \right) \frac{\partial F}{\partial v_i} \right] = 0$$

Consider a field-aligned potential $\phi$, of thickness $h$ aligned along $x_1$. Then

$$E_1 = -\frac{\partial \phi}{\partial x_1} \quad \quad E_2 = E_3 = 0$$

$$B_1 = B \quad \quad B_2 = B_3 = 0$$

The Vlasov equation becomes

$$\frac{\partial F}{\partial t} + \sum_{i=1}^{3} v_i \frac{\partial F}{\partial x_i} - \frac{e}{m} \frac{\partial \phi}{\partial v_1} \frac{\partial F}{\partial v_1} - \frac{e}{m} v_2 B \frac{\partial F}{\partial v_3} + \frac{e}{m} v_3 B \frac{\partial F}{\partial v_2} = 0.$$ 

If we choose

$$F = n \left( \frac{m}{2 \pi kT} \right)^{3/2} \exp \left[ -\frac{m}{2} \left( v_1^2 + v_2^2 + v_3^2 \right) \right] \exp \left[ -\frac{e \phi}{kT} \right]$$

and

$$\frac{\partial F}{\partial t} = 0.$$ 

Then

$$\frac{\partial F}{\partial v_1} = -\frac{m}{kT} v_1 F \quad \quad \frac{\partial F}{\partial v_2} = -\frac{m}{kT} v_2 F \quad \quad \frac{\partial F}{\partial v_3} = -\frac{m}{kT} v_3 F$$
and
\[
\frac{\partial F}{\partial x_i} = \frac{\partial F}{\partial \phi} \frac{\partial \phi}{\partial x_i} = -\frac{q}{kT} F \frac{\partial \phi}{\partial x_i} = -\frac{q}{kT} \frac{\partial F}{\partial x_i} \quad \text{for } i = 1
\]
\[= 0 \quad \text{for } i = 2, 3\]

Therefore, substituting in to the Vlasov equation
\[
0 + v_1 \left( -\frac{q}{kT} F \right) \frac{\partial \phi}{\partial x} - \frac{q}{m} \frac{\partial \phi}{\partial x} \left( -\frac{m}{kT} v_1 \right) F + \frac{qB}{m} \left[ -\frac{m}{kT} v_3 F_{v_2} - \left( -\frac{m}{kT} \right) v_2 F_{v_3} \right]
\]
\[= -\frac{q}{kT} v_1 F \left( \frac{\partial \phi}{\partial x} - \frac{\partial \phi}{\partial x} \right) + \frac{qB}{kT} F \left( v_2 v_3 - v_3 v_2 \right) = 0
\]

This proves that our form of the distribution function for the case of a field-aligned potential satisfies the Vlasov equation.

In the usual inverted V observed in the precipitating electron flux, the electric field points upward. In that case, the accelerated particles are the electrons and the decelerated particles are the protons. When the inverted V signature appears in the flux of precipitating protons, the accelerating electric field must point downward. This is what is inferred here, on AE-D orbit 1141.

The case of the upward electric field is illustrated in Figure 4.1 and the downward field in Figure 4.2. An immediate qualitative difference is evident in the accelerated species for each case. When protons are accelerated, there is a cutoff energy below which virtually no protons appear. When electrons are accelerated, a peak is evident for a given energy, but there are many electrons observed with energies below this peak.
Figure 4.1

Electron Inverted V

Upward Electric Field

Electrons Accelerated

Protons Decelerated

\[ \frac{E_2}{E_1} = \frac{0}{E_1} \]
PROTON INVERTED V
DOWNWARD ELECTRIC FIELD

PROTONS ACCELERATED

EATEG ST 1 2
\( \Delta \phi_p \)

E

ELECTRONS DECELERATED

log F

\( \Delta \phi_e \)

E
Since the distribution function $F$ is related to the differential flux $J$ by $F = \frac{m^2 J}{2E}$, the peak will be observed at a slightly lower energy in the plots of $\log F$ versus $E$ than in the $J$ versus $E$ plot. In the plot of $\log F$ versus $E$, the energy where the peak is observed corresponds to the energy received by falling through the potential. This result follows from Liouville's theorem and is illustrated in equation (4.3). This means that a particle which had zero energy at the top of the potential drop would receive energy equal to its charge times the potential drop. Thus, below the potential drop, virtually no protons would be observed at energies below the minimum energy $q\phi$.

The situation for an upward electric field which accelerates precipitating electrons is slightly different. Electrons backscatter from the atmosphere much more easily than protons. Basically, this is because they are 1800 times lighter than protons. In addition to these backscattered electrons, the precipitating particles will interact with the atmosphere, producing secondary electrons. Some of these secondaries are ejected so that they travel back up the field line. When the backscattered and secondary particles encounter the parallel potential drop, they are slowed down and turned around. These low energy electrons join the flux of precipitating electrons which have fallen through the entire potential drop. The low energy electrons fill in the electron spectrum below the peak energy. Calculations have shown that the energy degradation and generation of secondary particles from the primary electron flux agree with the observed spectrum below the peak (Pulliam et al., 1981).
Since the protons do not fill in below the peak, it is easy to determine the magnitude of the potential through which they fell. The distribution function shows a very clear cutoff, below which virtually no protons are observed (Fig. 4.3). The energy (read from a graph of log F versus E) of the channel which contains the proton cutoff will be called $\Phi_p$. Since the width of each channel is 3\% of its center energy, when $\Phi_p$ gets high, the uncertainty of exactly where the cutoff occurs reaches several keV. For this reason, $\Phi_p$ will be smoothed for some calculations. It will be noted in the calculation sections when this smoothing is performed.
Figure 4.3

LINEAR REGRESSION FIT TO OBSERVED DISTRIBUTION FUNCTIONS

\( (\sigma / \xi^s) \cdot F^{0|\delta|1} \)

\( E \) (keV)

\( \Delta \varphi_p \)
V. Calculations

The Parallel Potential Inferred from the Proton Cutoff

Figure 4.3 shows plots of the log $F$ versus $E$ for two different times. $F$ is the distribution function given by equation (4.2). These two observations were made sixteen seconds apart. Figure 4.2 illustrates how a downward-directed parallel electric field would affect the distribution function for protons. In Figure 4.2 the plot of log $F$ versus $E$ for time 1 (prior to acceleration) shifts to the right by $|e|\phi_p$. For the remainder of this discussion I will assume that the ions are protons and discuss both the energy shift and parallel potential in energy units of eV or keV. Equation (4.3) gives the distribution function for particles which have been accelerated by a parallel potential $\phi$. If the acceleration did not change the temperature, the graph simply moves to the right, as shown in Figure 4.2, and curve 1 becomes curve 2. In curve 2 there are no particles observed with energies below the potential $\phi_p$. I define $E_{co}$ to be the energy below which no protons are detected. In Figure 4.3 the data for 4:03:21 show a clear $E_{co}$. Almost every second of data throughout this event shows a similar cutoff energy.

Because the energy windows of the LEB stepped particle detectors are 31% (+17°, -14°) of the center energy, $E_{co}$ is uncertain by the same amount. This is the major error source in determining $E_{co}$. Figure 5.1 shows $\phi_p$, inferred from $E_{co}$. During the blank area at the center and at the three spiked peaks reaching 30 keV, the energy exceeded 28 keV, the
upper limit of the highest energy channel.

The Temperature and Density

Equation (4.2) may be rewritten to obtain the temperature (eqn. (5.1)) and the density (eqn. (5.2)). Figure 5.2 illustrates how a plot of \( \log_{10} F \) versus \( E \) depends on density and temperature. The temperature \( T \) may be calculated from

\[
T = \frac{1}{(2.3026 |S|)}
\]  
(5.1)

where \( S \) is the slope of the graph of \( \log_{10} F \) versus \( E \) and \( T \) is measured in keV. The density is calculated from

\[
n = F_I \cdot C_{nF} (kT)^{3/2}
\]  
(5.2)

where \( F_I = 10^I \) where \( I \) is the \( y \)-intercept of the curve \( \log F \) versus \( E \). If \( n \) is the density in number/cm\(^3\), \( F \) is in sec\(^3\)/m\(^6\), and \( E \) and \( kT \) are in keV, then

\[
C_{nF} = \left( \frac{2\pi m}{kT} \right)^{3/2} = 3.68 \times 10^{16} \text{ for } e^- \quad 4.67 \times 10^{11} \text{ for } p^+
\]

The density for the accelerated species (protons) may be calculated from the observations. For the decelerated species (electrons) the downward electric field moves the curve to the left. The resulting curve looks identical to one produced by a decreasing density. For the
Figure 5.2  (a) The slope \( S \) and \( y \)-intercept \( I \) of a plot of \( \log_{10} F \) vs. \( E \) are used in eqn. (5.1) and (5.2) to calculate the temperature and density.  
(b) This shows the distribution function of (a) after acceleration by \( \Phi_p \). The peak of the distribution function equals the old \( y \)-intercept of (a). This value may be used to calculate the source density (before acceleration).
electrons, either the decelerating potential or the density may be calculated; the other quantity must be assumed.

I have assumed that the ratio of electron densities at two different times changes like the ratio of the proton densities at those times. Using that assumption, I calculated the potential which decelerated the electrons. \( \Delta \phi_e \) is this decelerating potential, measured from a time of smallest decelerating potential. \( \Delta \phi_p \) is the accelerating potential referred to the same time. If electrons and protons passed through the same parallel potential \( \phi_t \), \( \Delta \phi_e \) should equal \( \Delta \phi_p \). This is simple electrostatic acceleration.

Figures 5.3 and 5.4 compare \( \Delta \phi_p \) and \( \Delta \phi_e \). For simple electrostatic acceleration, a plot of \( \Delta \phi_p \) versus \( \Delta \phi_e \) should have a slope of 1. Figure 5.3 displays data for section 1 and Figure 5.4 for sections 2.1, 2.2, and 2.3. The numbering of the sections corresponds to that on the spectrogram in Figure 3.1.

The electrons appear to be decelerated less than the protons are accelerated. Since the LEE detector measures energy/charge, a 2 keV \( O^{++} \) looks like a 1 keV \( P^+ \). Thus, ions of higher charge, which are accelerated more by \( \phi_t \), could not explain this extra ion acceleration.

The correlation coefficient \( r \) measures the goodness of fit of a linear correlation, being nearest zero when there is much scatter in the data. For a good correlation, \( r \) should be almost 1. In section 1 and section 2.3, the correlation is very poor \( (r = 0.3-0.4) \). In sections 2.1 and 2.2, the correlation is better \( (r = 0.8-0.9) \).
CALCULATED FIELD ALIGNED POTENTIALS

INCREASING $\vec{E}$

ELECTROSTATIC ACCELERATION

$r = 0.28$

$\Delta \phi_p \text{ kev}$

$\Delta \phi_e \text{ kev}$

Figure 5.3
CALCULATED FIELD ALIGNED POTENTIALS

DECREASING $E$

<table>
<thead>
<tr>
<th>Slope</th>
<th>$r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>5.7</td>
</tr>
<tr>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>2.3</td>
<td>2.4</td>
</tr>
</tbody>
</table>
Effect of Temperature Changes on F

A temperature increase flattens out the slope of a plot like figure 5.2. Figure 5.5 shows the temperature for the ions and electrons. The temperature was calculated from the slope of curves like Figure 5.2. Typical calculated ion temperatures are about 3-4 keV and fluctuate by about a keV. The values for high $\phi_i$ are more uncertain because fewer energy windows detect the increasingly energetic ions. The ions have been accelerated above the range of the lower energy windows. The electron temperature is about 500 eV and remains more constant.

Perhaps the precipitating electron population had been reduced to a background level of electrons which had not fallen through the entire field-aligned potential. Figure 5.8 suggests that this background is present. It may be secondary electrons produced by the primary ion flux. In the next section, I will reanalyze the data to reveal this possible background component.

Constant Energy Window "View" of the Distribution Function

As the parallel potential increases, the curve of log $F$ versus $E$ for electrons (the decelerated species) moves to the left (Fig. 4.2). Consider one energy step of the LEE detector, for example the energy window which has a center energy of 200 eV. As the log $F$ versus $E$ curve moves left, the 200 eV detector step will sample electrons of higher and higher source energy, above the parallel potential. Thus, a detector viewing a fixed energy window, will eventually sample the entire distri-
Figure 5.5

UT in sec after 4:03:00
bution. \( F \) and consequently \( \log F \) for a decelerated Maxwellian distribution is monotonically decreasing with energy. Eventually the Maxwellian distribution sampled by the 200 eV detector will have fallen below the background levels. Figure 5.6 illustrates how the increasing potential maps values of \( F \) for successively larger original energies into the 200 eV energy window. Thus, a plot of \( \log_{10} F(200) \) versus \( \phi_p \) should trace out the original distribution for electrons. Figure 5.7 shows the electron distribution function measured at 200 eV versus the accelerating potential inferred from the ion measurements. The line and dashed line show least square fits of \( y \) versus \( x \) and \( x \) versus \( y \). If the data showed no scatter, the two fits should produce the same line. A correlation coefficient is calculated: \( r = -0.74 \), which is a reasonably good correlation. Table 5.1 shows the correlation coefficients for the distribution function observed in a given energy window when \( \phi_p \) has a given value. In the second column, for a given \( \phi_p \), the observed \( F \)'s were averaged before the log was taken. In the third column, for a given \( \phi_p \), the average of the logs was correlated with \( \phi_p \). Results for two energy windows, centered at 200 eV and 273 eV, respectively, are shown. The log of the average \( F \) and \( \phi_p \) correlate best.

Figure 5.8 shows that for \( \phi_p \gtrsim 10 \) keV, the background flux of 200 eV electrons is independent of \( \phi_p \). This energy-independent flux makes our inferred \( \Delta \phi_e \) less correlated with \( \Delta \phi_p \), and may explain the discrepancy between \( \Delta \phi_e \) and \( \Delta \phi_p \). This background flux may be secondary electrons produced from the energetic ions striking the upper atmosphere.
Figure 5.6 As the potential inferred from the proton cutoff energy increases, the electron fluxes are depressed. The curve of log F versus E for the electrons moves to the left. If the temperature doesn't change, the slope remains the same. As the decelerating potential increases, the entire original distribution function in (a) marches past any fixed low energy window.
Figure 5.7

Electron 200 eV channel

$\log^{10} F (s^3/m^6)$ observed in

$\phi_p$ (keV) potential observed for protons

$r = -0.74$
We can see the electron fluxes depressed this much (to background level). For example, if $\phi_p$ changed from 5 to 30 keV, we would still detect the background flux of electrons. Thus, $\Delta \phi_e < \phi_p$.

The apparent electron deceleration is not as great as the proton acceleration.

Figure 5.8 The line is a least squares fit to $\log_{10} F$ versus E observed for electrons at time 4:03. The inferred parallel potential was then zero. The three points are data for this time which may indicate a high energy tail. The +'s are averages of the logF (observed for electrons in the energy window centered on 273 eV) when the parallel potential inferred from the proton data was $\phi_p$. 

Table 5.1

Linear Correlation Coefficient \( r \)

<table>
<thead>
<tr>
<th>channel</th>
<th>( \log F ) vs. ( \phi_p )</th>
<th>( \log &lt;F&gt; ) vs. ( \phi_p )</th>
<th>( &lt;\log F&gt; ) vs. ( \phi_p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>section 1</td>
<td>200 eV</td>
<td>-0.74</td>
<td>-0.88 -0.84</td>
</tr>
<tr>
<td></td>
<td>273 eV</td>
<td>-0.75</td>
<td>-0.86 -0.83</td>
</tr>
<tr>
<td>section 2</td>
<td>200 eV</td>
<td>-0.63</td>
<td>-0.77 -0.76</td>
</tr>
<tr>
<td></td>
<td>273 eV</td>
<td>-0.63</td>
<td>-0.76 -0.75</td>
</tr>
</tbody>
</table>

Calculation of Electric Fields

The electric field at the satellite may be calculated from the velocities measured by the Drift Meter (DM) and the Retarding Potential Analyzer (RPA) and from a model magnetic field. The measurement of velocities was described in section 2. Figure 2.3 shows the \((x,y,z)\) coordinate system used for the velocity components. Figure 5.9 shows the horizontal velocities, \(v_x\) and \(v_z\). The \(y\) and \(z\) components show a periodic wobble, due to satellite nutation. A five point running average was performed on \(v_y\) and \(v_z\) to remove the nutation effects. The RPA supplied \(v_x\). Where the RPA did not have the required data to determine \(v_x\), intermediate values were determined by linear interpolation. The electric field \(E\) in volt/m = \(10^{-4} \cdot B \times \mathbf{v}\) where \(B\) is in Gauss and \(\mathbf{v}\) is in m/sec. Figure 5.10 shows the calculated electric field.
Calculation of the Potential Profile at the Ionosphere

The potential profile at the ionosphere $\phi_I$ may be calculated from the electric fields shown in Figure 5.10. $\phi_I = -\int E_x \cdot dx$. This potential inferred at the ionosphere is shown in Figure 5.11. This is not the total polar cap potential drop. Continuation of this integration gives 52 keV potential along the satellite path up to the estimated polar cap boundary. This is a lower bound for the total polar cap potential drop. $\phi_{total}$ is the sum of $\phi_p$ (inferred from the ion data) and $\phi_I$. Figure 5.11 shows how the parallel potential decoupled the potential in the magnetosphere ($\phi_{total}$) and the potential in the ionosphere ($\phi_I$).

By decoupling the potential in the ionosphere from that in the magnetosphere, the field-aligned potential reduced the potential, hence the horizontal electric field, seen by the ionosphere. Thus, the ionospheric Pedersen currents are reduced. The divergence of these Pedersen currents feed the Birkeland currents. The ionosphere may now sustain this smaller Birkeland current. A rough calculation indicates that the ionosphere can only provide currents up to about 6 $\mu$A/m$^2$, since the ionospheric Pedersen currents are caused by ions whose thermal current is approximately that value. Figure 5.15 shows that the maximum downward current required for balance is about 6-8 $\mu$A/m$^2$. This could be provided by upward-moving ionospheric electrons.
Figure 5.11

UT in sec after 4:03:00

$\phi(\text{keV})$

$\phi_{\text{total}}$

$\phi_{\text{inferred at ionosphere}}$
Calculation of Hall and Pedersen Conductivities

The current flowing on a field line \( J_H \) may be calculated from the horizontal divergence of the dot product of the electric field \( E \) and the conductivity \( \Sigma \).

\[
J_H = \nabla_H \cdot (\Sigma \cdot E)
\]  
(5.3)

\( \Sigma \) is a tensor conductivity. The component of this tensor which is associated with a current flowing perpendicular to the magnetic field and parallel to the electric field is the Pedersen conductivity. The conductivity associated with a current in the \(- (E \times B)\) direction is the Hall conductivity.

Empirical formulae for height-integrated Hall and Pedersen conductivities were given in Harel et al. (1981).

\[
\Sigma_p = (5.2 \text{ mho}) \left[ \frac{\text{Energy flux}}{\text{erg/cm}^2\text{-sec}} \right]^{1/2}
\]  
(5.4)

\[
\Sigma_H = (0.55) \left[ \frac{\text{Average } e^- \text{ energy}}{\text{keV}} \right]^{0.6} \Sigma_p
\]  
(5.5)

Here \( \Sigma_p \) is the height-integrated Pedersen conductivity and \( \Sigma_H \) is the height-integrated Hall conductivity.

Because the event occurred in sunlight, it was necessary to calculate the contribution of EUV ionization to the conductivity. Vickrey et al. (1981) have empirically determined the photoelectron Pederson \( \Sigma_p^{\text{ph}} \)
and Hall ($\Sigma_H^{ph}$) conductivity dependence on the solar zenith angle $\chi$.

$$\Sigma_p^{ph} = 6 \cos^{1/2} \chi$$

(5.6)

$$\Sigma_H^{ph} = 10 \cos^{1/2} \chi$$

(5.7)

where $\chi$ is measured in degrees and $\Sigma$ in mhos. Wallace and Budzinsky (1981) found that $\Sigma_T$, the total conductivity due to both precipitating particle fluxes ($\Sigma_p$) and sunlight ($\Sigma_s$), may be approximated as

$$\Sigma_T = \left[ \Sigma_p^2 + \Sigma_s^2 \right]^{1/2}$$

(5.8)

The $\Sigma$'s are either Hall or Pedersen conductivities. This approximation is good to 15% for $\Sigma_H$ and 7% for $\Sigma_p$.

Figures 5.12 and 5.13 show the Pedersen and Hall conductivities calculated for this event. The energy flux and average electron energy for equations (5.4) and (5.5) were calculated from the observed electron fluxes.

This does not include contributions from the ion flux. Ion energy fluxes of this magnitude (approaching one erg/cm$^2$-sec) can cause substantial ionization (Reiff, 1983a).

I searched DMSP photos and inquired about all sky camera data for conjugate locations in the northern hemisphere. No data were available (Burrows, personal communication, 1983).
Figure 5.13

UT in sec after 4:03:00
Comparison of the Current Calculated from the Divergence of the Electric Field and from the Observed Particle Fluxes

Equation (5.3) was used to calculate a current using the conductivities from equation (5.8) and the electric field shown in Figure 5.10. The upward current calculated from the observed precipitating electrons was calculated from the observed number fluxes. Figure 5.14 shows these two currents. The current carried by the precipitating ions was not visible on this scale. The two methods agree on the location of Birkeland (field-aligned) currents, but differ in magnitude. This is not surprising for two reasons. First, only the component of the divergence along the satellite track was included in $\nabla \cdot (\mathbf{E} \cdot \mathbf{E})$.

I had attempted to include part of the variation perpendicular to the orbital track by noting that $\nabla \times \mathbf{E} = 0$ when $\partial B/\partial t = 0$. This did not improve the agreement of the two methods for calculating Birkeland current.

The extra current might be carried by upward-moving electrons. They could carry a balancing downward current. No LEE detectors looked down, so these electrons could not have been detected. Figure 5.15 shows the current needed to balance the current inferred from $V_H \cdot (\mathbf{E} \cdot \mathbf{E})$ with the current carried by precipitating electrons. Figure 5.16 shows the electron anisotropy this would require. In both figures, negative values indicate that upstreaming electrons could not provide a balancing current.

The maximum downward current which the system requires upward-flowing ionospheric electrons to provide is 6-8 μAmp/m² (Fig. 5.14).
Figure 5.14

$J_{\text{inferred}}$

from $\text{div}[\mathbf{E} \cdot \mathbf{E}]$

BIRKELAND CURRENT (ampere/meter$^2$)

downward

$J_{e^-}$

UT in sec after 4:03:00
Figure 5.15

UT in sec after 4:03:00

Ionospheric $e^- \text{(amp/meter}^2\text{)}$ which would balance the observed J of precipitating particles with J inferred.

Downward

Minus is no balance
ELECTRON ANISOTROPY WHICH WOULD BALANCE CURRENTS

Figure 5.16

UT in sec after 4:03:00

minus is no balance
This is apparently the maximum current which the ionosphere can sustain, and agrees with rough calculation of the maximum current which can be drawn from the ionosphere.

This suggests that ion inverted V's form when current demands would force the ionosphere to produce more current than it can sustain. The current demands may be lowered by dropping some potential via a parallel electric field. This causes the ion inverted V.

The downward electric field also reduces the upward current by turning off the precipitating electrons. The albedo of a precipitating electron is less than one (Hill et al., 1983), so this reduces the downward current required for balance.
VI. Alternate Explanations

This thesis analyzes the data under the assumption that the precipitating particles have fallen through a field-aligned potential drop. During discussions, several other mechanisms have been suggested. The four major alternatives follow: (1) spacecraft charging; (2) contamination by electrons; (3) topside echo of a conjugate electron inverted V; and (4) particle origin in the tail. I will consider each separately.

**Spacecraft Charging**

During this event, the spacecraft altitude varied between 790 and 650 km. It was sunlit and the spacecraft was immersed in an ambient plasma of density around $10^4$ particles/cm$^3$. Charging due to the emission of photoelectrons would produce a spacecraft potential that would tend to repel ions, rather than accelerate them. Although a spacecraft in the less dense plasma of geosynchronous orbit might charge up to a few keV, AE-D was surrounded by much higher density plasma where total charging potentials are only a few tenths of a volt. AE-D could not maintain keV spacecraft charges at those densities. Spacecraft charging cannot explain a 28 keV potential, corresponding to a downward electric field.
Contamination of the Ion Detector by Electrons

The LEE ion detector excludes electrons in two ways. First, a suppressor grid applies a potential to repel electrons. Second, even if an electron passed the suppressor grid, its negative charge would cause it to be deflected toward the outer wall of the cylindrical electrostatic analyzer inside LEE.

A large population of very energetic electrons might overcome the suppressor voltage and a few might bounce off the walls of the analyzer, eventually reach the detector, and produce counts. This has only been observed when looking in the ram direction, at perigee (< 200 km altitude). The electron detectors should have shown this energetic electron population; they did not. Furthermore, the particles observed in the ion detector did not peak at low energy. They showed a clean low energy cutoff. Also, the flux observed by the electron detectors decreased as the ion detector observed increasingly energetic fluxes. These points indicate that it is unlikely that electrons contaminated the LEE ion detector.

Topside Echo of a Conjugate Electron Inverted V

This thesis postulates that the ions were accelerated by a downward-directed electric field. The Dynamics Explorer (DE) satellite has observed an upward directed beam of ions above an electron inverted V (Winningham et al., in preparation). If such an electron inverted V existed in the northern hemisphere, the ions could flow along the con-
necting field line to the southern hemisphere. Because the ions are so massive, they would have time to convect equatorward during their transit along the field line. Even though similar inverted V's tend to exist on the same field line in conjugate hemispheres, the ions would have convected equatorward of any southern hemisphere inverted V, and avoided its upward-directed electric field. Thus, the ions would not have been decelerated by another electron inverted V in the southern hemisphere. They could have retained the acceleration received from the original electron inverted V (Fig. 6.1).

This is an interesting idea, but does not appear to be the interpretation for these data, for two major reasons. First, the ion fluxes did not show any dispersion. If the ions traveled from the northern hemisphere, the most energetic ions would have arrived first, followed by the lower energies.

But in the first half of the large ion inverted V, the most energetic ions arrived last. Second, the satellite was in a region of antiserward convection. If the ions traveled from the northern hemisphere, they convected equatorward. This means that the hypothetical electron inverted V occurred in the northern hemisphere at an even higher latitude.

The observed event occurred at southern invariant latitudes of 72° to 75°. At the end of the event, the satellite entered the polar cap, as evidenced by the absence of ions and the reduced electron fluxes, characteristic of the polar rain. Mapping the observed ions' motion backward to the northern hemisphere would probably place the required electron inverted V in the northern polar cap. Electron inverted V's do
not often form in the polar cap, except in quiet times. The magnitude of the storm suggests that this interpretation is not likely.

**Particle Origin in the Tail**

This explanation is also unlikely because again the ions do not show dispersion. If they were accelerated out in the tail, the most energetic ions should have arrived first. During the first section of the ion inverted V, dispersion definitely did not occur.

Compared to these four alternatives, a downward-directed parallel electric field above the AE-D spacecraft better explains the data.
VII. Theory of Acceleration Mechanisms

This thesis has presented evidence that a downward parallel electric field \( E_{\parallel} \) has developed and accelerated particles to produce an ion inverted V. The mechanism which sustains a parallel electric field has not yet been identified. I will describe six methods which might maintain an electric field parallel to the magnetic field lines.

**Double Layer**

The name "double layer" connotes a layer of electrons lined up opposite to a layer of protons. While this certainly produces an electric field, the configuration must be self-consistently supported in a current-carrying plasma. The double layer can energize particles passing through it. For instance, a double layer corresponding to a downward \( E_{\parallel} \) would produce downward streaming ions below the double layer and upward streaming electrons above it. The energy given to these particles by the double layer is provided by an external electromotive force (emf). The details of how this force transfers the energy to the particles at the double layer vary among different theories. However, it is generally believed that the source for the potential drop on auroral field lines must be the emf generated by the magnetospheric convection. Thus, the ultimate energy source is the solar wind. A caveat follows: in order to model a region of field lines narrow in latitude, such as an active discrete arc, the emf might be generated from ionospheric convection rather than directly from the magnetosphere (Sato,
1978; Miura and Sato, 1980; Kan and Lee, 1981). But in a more comprehensive model encompassing all of the ionosphere, the energy for this ionospheric convection would derive from the magnetospheric convection.

At least five different kinds of double layers have appeared in the literature (Lewis Carroll, 1872): lab double layer; auroral double layer; Debye-length double layer; unmagnetized double layer; and magnetized double layer.

Double layers were first recognized in the laboratory. It was later suggested that they might maintain a parallel electric field responsible for auroral acceleration. The use of the term "lab double layer" often means that the author does not think that a double layer must be greatly modified to accurately model the auroral potential. In the laboratory when two plasmas with different thermal velocities contact each other, a double layer develops to maintain a potential drop of the magnitude of $kT_e/e$ between the plasmas. This double layer acts to match the two plasmas. A weak double layer forms where the cross section of the confining tube changes. It does not require a minimum current density.

In a tube of uniform cross section a stable double layer will form if the plasmas satisfy the Bohm criterion. The Bohm criterion specifies that the minimum electron drift velocity entering the double layer must be at least as great as the thermal electron velocity. Since this is required in order to maintain quasi-neutrality, the actual velocity may be lowered by the presence of trapped electrons on the high potential side of the double layer. These electrons must have energies up to the double layer potential. The injected particle distributions for lab
simulations do not approximate those observed in the aurora.

Early laboratory experiments did not include a magnetic field. The scale length for the lab double layer without a magnetic field is on the order of the Debye length, $\lambda_D$. The scale length of a magnetized double layer may involve the ion gyroradius. In the aurora the ion gyroradius $\rho_{ei} \gg \lambda_D$. In the aurora the scale length for the converging magnetic field lines or the distance over which turbulence can dissipate the energy may affect the double layer scale length (Kan and Lee, 1981).

Some lab simulations have included a magnetic field strong enough to magnetize the electrons. The electron gyroradius is smaller than the dimensions of the plasma. The ion gyroradius exceeds the plasma so the ions are unmagnetized (Block, 1981). Energy transfer due to ion cyclotron waves would not show up in these simulations, although these waves may be important in the aurora.

In summary, double layers definitely exist in the laboratory, but the conditions in a real aurora differ in possibly critical ways:

1. Lab double layers have a smaller Debye length.

2. The scale length for a lab double layer has a much simpler dependence on plasma parameters than a real double layer in the aurora.

3. Many lab simulations used unmagnetized plasma or at best magnetized electrons.

4. The lab conditions may exclude waves which are important for wave-particle interactions in a double layer in the aurora.

5. The velocity distributions injected for the laboratory double layer are not realistic for the aurora.
I have discussed one of the five varieties of double layer and touched upon three others. The Debye-length double layer may refer to the fact that laboratory double layers scale with the Debye length, or it may refer to a computer simulation of a Debye layer which includes physics resulting in scaling with the Debye length. The term is usually used to point out that such a double layer does not fit auroral conditions. Similarly, an unmagnetized double layer refers to a model which has omitted the effects of the magnetic field.

Finally, Lee and Kan (1981) have defined the auroral double layer operationally. The auroral double layer is an extended region of electric potential observed on field lines above the aurora. Operationally, the potential structure exists along a field line for distances of several Earth radii. It is then possible to ask a question such as: "Do auroral double layers adequately model the acceleration mechanism for large scale auroral arcs?" In my opinion, the answer is not necessarily "yes." For example, if in the real situation more than ten percent of the energy received by the particles was transferred by wave-particle interaction or by another mechanism which depended on anomalous resistivity (discussed later), the preceding question must be answered "no." Otherwise, auroral physics has been performed by definition, instead of by science.

Ultimately, the five varieties of double layer may be reduced to two major types: the lab double layer and the auroral double layer. The next sections discuss five more methods which could create a parallel electric field. These mechanisms are not mutually exclusive with double layers or with each other.
Electrostatic Shocks

Kan and Lee (1981) define an electrostatic shock to be "potential structures self-consistently supported in a streaming plasma." Just from that, it is not immediately obvious how electrostatic shocks differ from double layers. The papers by Kan (1975) and Swift (1975) introduced the term "electrostatic shock" to auroral physics. Unfortunately, Kan's model was actually a combination of double layer and shock and Swift's model was an oblique double layer. This has led to confusion in subsequent papers. Models of electrostatic shocks differ from models of double layers in two major ways. Double layers have net electrical currents, but electrostatic shocks do not. Double layers get energy from an external emf, while electrostatic shocks get energy from one of the particle species which streams through the shock (Kan, 1980).

Satellites have observed abrupt discontinuities in the electric field at several Earth radii. S3-3 observations indicate that a potential distribution exists at altitudes of 5,000 km to 10,000 km (Gorney et al., 1981). This has been interpreted as the observation of electrostatic shocks. It is confusing when compared to the papers written by those who believe in double layers. Kan and Lee (1981), Lee and Kan (1981), and Block (1981) dismiss electrostatic shocks. For example, they claim shocks scale with the Debye length, while the observed potential distribution seems distributed over the field line for much greater distances. This may mirror the situation of lab double layers versus auroral double layers. Chiu et al. (1981) discuss four methods for auroral acceleration, including Debye-length double layers and oblique
electrostatic shocks. In this sense the electrostatic shock is more a hybrid with a double layer, than it is a pure electrostatic shock. Also, Hudson and Potter (1981) begin a paper entitled, "Electrostatic Shocks in the Auroral Magnetosphere," with the words, "We present a 1d unmagnetized double layer simulation..." Lyons (1981) considers three mechanisms: anomalous resistivity, single particle motion, and the double layer/electrostatic shock. The latter is considered as one mechanism. Thus the functional meaning of double layer versus electrostatic shock differs even among the most important papers summarizing current observations and theories of auroral acceleration mechanisms.

**Single Particle Motion**

Lyons (1979, 1980, 1981) calculates the parallel current $j_\parallel$ and parallel potential $\phi_\parallel$ along auroral field lines. He lists the relevant mechanisms as single particle motion, anomalous resistivity, and finally Debye layer/electrostatic shock. He discounts anomalous resistivity as being unnecessary, and discounts the Debye layer/electrostatic shock mechanism because observations do not show that $\phi_\parallel$ results from $j_\parallel$ reaching a critical value that cannot be exceeded.

Early theories argued against the existence of parallel electric fields because the conductivity along $B$ was considered to be infinite. Thus, particles could move freely along $B$ to short out any parallel electric field which began to develop. Later models explained the existence of parallel electric fields by proposing the existence of some unexpected resistivity (caused by collective phenomena) along the field
line, which prevented the particles from shorting out the parallel potential. Lyons claims that anomalous resistivity is a red herring because the field line is not infinitely conducting in the first place. It appears infinitely conducting because a formula (Spitzer, 1962) for the resistivity from Coulomb collisions was used outside its range of validity. Lyons claims that this equation is not valid under auroral conditions, which often show 1-10 kV potential differences along the field line. The equation should be used only if the particles' thermal energy completely dominates the energy transferred between collisions to the particles by the electric field. Essentially, the current which can be carried by a plasma in a converging magnetic field is limited to the thermal flux, unless a parallel potential drop is established. The current-voltage relationship is readily calculated (Knight, 1973; Yeh and Hill, 1981). An effective "resistivity" results, but it is not anomalous and does not require collective effects such as waves. Lyons' calculations apply to latitudinal scale widths of about 200 km. This is comparable to broad inverted V regions. With the addition of structure to the potential distribution high in the magnetosphere, single particle motion can model discrete aurora of tens of km latitudinal width. The 10 km width corresponds to homogeneous discrete arcs. Additional mechanisms must be important in the active arcs of 100 m width. For example, Kan and Okuda (1983) suggested that electron beams formed by inverted V's can go unstable, resulting in smaller-scale structures.
Anomalous Resistivity

Anomalous resistivity is a resistivity in excess of that expected from binary particle collisions. It inhibits the motion of particles along a field line and allows the development of parallel potentials.

When the fields of unstable waves in a collisionless plasma scatter current carrying electrons, the waves produce anomalous resistivity. Electrostatic ion cyclotron waves have been observed in the auroral zone near 1 R_E altitude and could provide the anomalous resistivity (Kan and Lee, 1981; Kintner et al., 1979). The latitudinal width of the resulting E|| scales with the ion cyclotron radius. This size corresponds to auroral arcs embedded in an inverted V region.

The next two mechanisms, without doubt, exist on auroral field lines. Sometimes they are incorporated in models primarily labeled by the preceding four mechanisms. These two remaining mechanisms are differential pitch angle anisotropy and the thermoelectric process. Model calculations attempt to determine whether these two are important enough to require inclusion in theories of auroral acceleration, and whether they are sufficient. (Can they transfer as much energy to the particles as is observed in the accelerated particle flux?)

Differential Pitch Angle Anisotropy

If the pitch angle distribution for electrons differs from that of ions out in the magnetosphere, when the particles reach a region of converging magnetic field, they can generate a parallel potential. This is
basically because particles of different sign are mirroring at different altitudes. The resulting potential is extended along the field line for distances much larger than the Debye length. The thermal energy of the anisotropic particles provides energy for acceleration. In the simplest model, the maximum parallel potential which can result is limited by the thermal energy of the colder species (Alfvén and Fälthammar, 1963; Kan and Lee, 1981).

**Thermoelectric Process**

This process resembles the formation of weak double layers in the laboratory. Two plasmas of different temperatures mix and set up a parallel potential because the hotter species is more mobile. In the auroral region, the magnetospheric electrons are hotter than the ionospheric electrons. This leads to a downward electric field (Hultqvist, 1971, 1972; Kan and Lee, 1981). This process would inhibit the formation of electron inverted V's and enhance the formation of ion inverted V's. Again, however, the maximum potential differences are on the order of the thermal energies.
VIII. Summary

The energy-time spectrogram from AE-D for January 11, 1976 shows an ion inverted V. As the ions were accelerated to over 28 keV, the electron flux was depressed. Simple electrostatic acceleration predicts that ion acceleration equals electron deceleration. These energy changes were correlated, but not equal. The electron flux which passed through a parallel potential may have been depressed below a background of electrons, created below the potential region.

The field-aligned (Birkeland) current at an inverted V may be calculated either from the divergence of the electric field or from the observed particle fluxes. These two methods predict current flow in the same location, but differ in calculating the magnitude of the currents. The currents may be balanced either by upward flowing electrons or by the component of $\nabla_H (\mathbf{v} \cdot \mathbf{E})$ which is perpendicular to the satellite track.

The inferred parallel potential decoupled the ionosphere from the magnetosphere. If a parallel potential had not developed, the potential in the ionosphere would have been much larger. The currents required from the ionosphere would have exceeded the maximum which it can provide.

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