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OBSERVED IN THE MAGNETOSPHERE AND
THE MAGNETOTAIL.

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AURORAL ZONE ELECTRON PRECIPITATION ASSOCIATED WITH ELECTRON BURSTS OBSERVED IN THE MAGNETOSPHERE AND THE MAGNETOTAIL

by

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1. INTRODUCTION

A. The Magnetospheric Substorm

The interaction of the solar wind with the geomagnetic field produces a number of distinctive and unusual phenomena. Perhaps the most significant of these is the confinement of the magnetosphere and its extension into a geomagnetic tail. In addition to this quasi-static interaction there are often large scale and transient variations in the geomagnetic field produced directly, or indirectly, by changes in the solar wind. These large scale "magnetic storms" can drastically alter the trapped particle environment, cause large scale plasma variations in the magnetotail, initiate violent auroral activity, and manifest themselves in a multitude of ways. That these magnetospheric and auroral phenomena are related in a complex and uncontrollable manner has understandably delayed a complete description of the "magnetospheric substorm." Any description must necessarily explain the relations and correlations between the various auroral and magnetospheric phenomena. Many cause-and-effect relations have been established but a complete description of the magnetospheric substorm is far from being complete.
B. The Auroral Zone

The various manifestations of the auroral phenomena have been extensively studied for many years. It was known as early as 1845 that a correlation existed between the visual aurora and magnetic variations observed on the earth's surface (Burritt, 1845). Birkeland, (1896) as a result of a series of classical terella experiments proposed that corpuscular bombardment of the atmosphere was in some way responsible for the aurora. The corpuscular origin of the aurora was further substantiated by the theoretical work of Stormer, (1912). Although Stormer's work has subsequently been shown to be more applicable to cosmic ray particles than to auroral particles, he was able to demonstrate the magnetic control of particle motions. All of these early experiments indicated that auroral spatial morphology was determined primarily by the geomagnetic field. Another important result of Stormer's work was that he was able to predict a cutoff latitude below which solar particles could not reach the earth's atmosphere. This cutoff latitude defined circles which were concentric about the magnetic poles and were observed to roughly coincide with the latitudes of maximum auroral activity.

Davis (1962) made an extensive statistical study of the alignment and distribution of auroral arcs over the whole polar sky. This detailed statistical study was based on the daily variations of auroral features observed at a single station. By combining the average characteristics obtained in this study he was able to define the morphological features of the auroral displays over the entire polar region. He concluded that the auroral zone is a wide belt which completely encircles the magnetic poles and thus substantiated the earlier suggestion that the aurora tend to lie in an "aurora oval." (See Feldstein, 1966 for a review.)
More specifically, the position of the auroral oval is based on a statistical analysis of the latitudinal variation of the auroral occurrence frequency. The probability of seeing an aurora was taken to be the ratio of the number of half-hour intervals with an aurora at the zenith to the total number of intervals under observation, with the added assumption that there were good seeing conditions, or in other words, that one could see an aurora if it were indeed present. The classically defined auroral oval in which the probability of auroral occurrence exceeds 70% per half hour is shown in Figure 1, (from McDiarmid and Burrows, 1967).

The auroral oval is not a stationary feature of the auroral zone. Its position is observed to be strongly dependent upon the amount of local magnetic activity present, (Basler, 1963, Chapman, 1964, Davis, 1962, and Feldstein and Starkov, 1967). The relationship of auroral activity to the local magnetic index, (the Q index), rather than the planetary indices Qp and Kp, led Akasofu, (1964) to suggest the term "auroral substorm." This concept of the auroral substorm was introduced to describe the characteristic forms of the auroras at various times and longitudes after the "break-up" of the auroral arcs around local magnetic midnight. The term substorm indicates that auroral disturbances are related to the long-lived geomagnetic main-phase storm. The dependence of the auroral oval upon magnetic activity is shown in Figure 2, (after Feldstein-Starkov, 1967).

It is important to note at this point, in anticipation of the next section, that the maximum auroral activity occurs around midnight and that the daytime auroral zone is rarely observed at latitudes above 78°. It can also be seen from Figure 2 that for moderate values of the Q index, the average position of the nighttime auroral belt is located at approximately 67°. Since the most
violent auroral activity occurs around local midnight, this interpretation accounts for the classically defined auroral zone latitude of 67°.
C. The Magnetosphere

Although the general configuration of the geomagnetic surface field has qualitatively been understood for sometime, it has been only within the last 50 years that the extent and distortion of the geomagnetic cavity has been investigated. Birkeland, (1908), again as a result of his terella experiments was the first to suggest that the earth's geomagnetic field would be confined by the solar plasma. Some of the earlier theoretical calculations of the distorted geomagnetic field were made by Chapman and Ferraro, (1931). They were able to predict the position of the magnetopause at the subsolar point as well as the two neutral points on the noon meridian. They also suggested that solar plasma was somehow injected into the neutral points on the noon meridian and eventually precipitated into the earth's atmosphere in the auroral zone. Their model, and that of Axford and Hines, (1961) predicted that the aurora would be a daytime phenomena due to the location of the neutral points. These and other early models of the magnetosphere also predicted that the geomagnetic field on the night side of the earth would be distorted but would not form a tail, (Johnson, 1960).

In addition to the difficulty these theories had in explaining the nighttime aurora, recent calculations by Mead, (1964) have shown that the field line from the neutral point intersected the earth between 80° and 85° as the subsolar distance to the magnetopause changed from 5 to 15 $R_E$. Since the daytime aurora are observed well below these latitudes (Davis, 1962 and Ansari, 1964), it was proposed by Dessler and Juday, (1965) that the inclusion of a quiet-day ring current would lower the neutral-point field line latitude to the observed latitude of quiet-day auroras. Using a self-consistent technique and including a quiet-day ring current field, Schild, (1968) was able to show that the
surface latitude of the neutral point field line did not move substantially and further, that the dayside aurora occurred on field lines which closed within the magnetosphere.

With the advent of the rocket as a research tool man acquired the capability of measuring his particle and field environment to great distances in space. As more flights were made, and data were accumulated, the extent and character of the geomagnetic field were more precisely defined. Even as early as 1958 the sunward side of the magnetosphere was being investigated by Pioneer I. These measurements indicated that the near-earth field was approximately dipolar and that there quite probably was an outer boundary of the geomagnetic field (Sonett et al., 1960 a, c). The existence of the ring current associated with magnetic storm main phase disturbances was implied in the magnetic field measurements made in 1959 on the Russian satellites, Luniks I and II, (Dolginov et al., 1960, 1961 a, b). Later measurements over wider regions of the magnetosphere and larger radial distances made by Explorer 6 and Pioneer 5 also indicated an approximately dipolar field and an implied outer boundary of the magnetic field, (Smith et al., 1960, Sonett et al., 1960 b and Coleman et al., 1960 b, 1964). Measurements confirming the existence of the magnetopause and an extended geomagnetic field on the night side of the earth was first made by Explorer 10 in 1961. With the refined measurements made by Explorers 10 and 12, the interpretation of the data obtained in the earlier exploratory flights of Pioneer I and 5 and Explorer 6, were placed in proper perspective and the existence of a permanently confined geomagnetic field was firmly established.

The relation between trapped particles and the geomagnetic field at the magnetopause was first investigated in 1961 by Freeman et al., (1963), and
Cahill and Amazeen, (1963) using Explorer 14 data. Using electron measurements made by Explorer 12 Freeman, (1964) showed evidence supporting the existence of plasma accumulation beyond the magnetopause.

Since the first rocket flight in 1958 a multitude of papers, in addition to those given here, have expounded upon the various features of the geomagnetic field and the radiation contained therein. The pertinent features of the magnetospheric model evolving out of this research are shown in Figure 3, (from Ness, 1966).
D. The Magnetotail

A whole new generation of auroral theories began to develop when it was realized that the earth's magnetosphere should have a tail of magnetic field lines stretched out in the anti-solar direction by the action of the solar wind, (Piddington, 1960, Johnson, 1960, and Axford and Hines, 1961). These new theories elaborated upon the role that the newly discovered magnetotail might play in geomagnetic storms and in the general character of the earth's total particle and field environment.

To avoid the apparent problems of the closed tail models of the magnetosphere, Dessler and Juday, (1965) proposed an open-tail field model which would be blown open by hydromagnetic waves (Dessler, 1964) and would extend several astronomical units in the antisolar direction. In their model, the auroral zone was taken to be the equatorward boundary of the open-tail field lines and thus they were able to predict oval shaped auroral zones on the earth's surface. The magnetotail of their model shown in Figure 4, consisted of two tubes of flux separated by a neutral sheet through which there was no magnetic merging. Subsequent observations of the magnetotail by Explorer 10 (Heppner et al., 1963) and an extensive survey of the night side geomagnetic field by IMP-1 indicated clearly its tail-like structure and region of field reversal, termed the "neutral sheet", (Ness, et al., 1964, Ness, 1965).

Recent satellite measurements have extended our knowledge of trapped particles in the earth's magnetotail considerably beyond the quasi-stable Van Allen Belts, (Armstrong and Krimigis, 1968, Montgomery, 1968, Murayama and Simpson, 1968, Lazarus et al., 1968). Magnetic field measurements made by the Pioneer 7 satellite have shown that remnants of the earth's magnetotail extend to a distance of at least 1000 RE in the anti-solar direction, (Fairfield,
1968). The general results of these and similar measurements can be summarized as follows:

(a) Energetic particles, particle "islands" and magnetotail plasma tend to be observed near the geomagnetic equatorial plane for radial distances $< 12 \text{ RE}$ (Montgomery et al., 1965, Anderson, 1965, Frank, 1965), near the solar ecliptic for radial distances $> 25 \text{ RE}$ (Anderson, 1965, Fan et al., 1965, 1966a, Lazarus et al., 1968), and at regions of space intermediate to the locations of these two planes for $12 \text{ RE} \leq r \leq 25 \text{ RE}$ (Anderson et al., 1965, Murayama, 1966, Bame et al., 1967).

(b) Rapid increases in the energetic particle fluxes or "islands" exhibited no clear tendency to occur near the geomagnetic neutral sheet. (Anderson, 1965).

(c) The frequency of occurrence of these increased energetic particle fluxes tends to decrease with increasing radial distances (Anderson, 1965).

(d) At Vela orbits in the magnetotail ($\sim 18 \text{ RE}$) energetic particle fluxes exhibit a dawn-dusk asymmetry with the fluxes being more intense in the midnight-dawn sector, (Bame et al., 1967, Montgomery, 1968).

(e) The "plasma sheet" extends from the dawn to the dusk magnetopause and is typically observed to have a thickness of 6-8 RE during quiet magnetic periods (Bame et al., 1967, Montgomery, 1968).

(f) The plasma sheet is observed as close to the earth at $6.6 \text{ RE}$ (Freeman and Maquire, 1967, Vasyliunas, 1968) and $> 30 \text{ RE}$ in the magnetotail.

The regions of energetic particle distributions in the magnetotail are shown in Figure 6. (From Murayama and Simpson, 1968, based upon Figure 5 by Speiser and Ness, 1967.) An inherent feature of all auroral theories in vogue at the time of these measurements was that the auroral zone was still defined
by the geomagnetic field configuration. More specifically, by the boundary between the field lines which were closed within the magnetosphere and those field lines which opened out into the tail.

After the discovery of the magnetotail plasma and neutral sheet it became apparent that any auroral theory would require the specification of the magnetospheric electric and magnetic fields. Another premise of the Axford and Hines, (1961) theory was, that in addition to stretching out the tail the interaction of the solar wind at the magnetospheric boundary would also cause convection of plasma within the neutral sheet. By assuming a merging of the solar wind magnetic field with the magnetosphere Dungey, (1961) was able to arrive at essentially the same conclusion. In Dungey's model of the magnetosphere it was postulated that merging of the solar wind and magnetospheric field lines at the magnetopause would result in the merging of the magnetotail field lines across the neutral sheet (see Figure 5). Applying the frozen-in flux concept this merging would then result in a flow of plasma out of the merging region toward, (and away from), the earth. Whether the cross-tail electric field is due to field line merging, or some other mechanism, such as those proposed by ALfven, (1939), Axford and Hines (1961), or ALfven, (1968) is not relevant, but it is essential that such a field exists.

Using the concepts of a cross-tail electric field and frozen-in flux Axford et al., (1965), Atkinson, (1966), and Axford, (1966) proposed that plasma in the magnetotail would be carried into the auroral zone causing polar disturbances. In addition, it was suggested (Axford et al., 1965, Coppi, 1966, Speiser, 1965, 1967, and Kavanagh et al., (1968) that auroral particles would be energized and that the trapped particle environment would also be affected (Brice, 1967). The role of the magnetosphere, and particularly the magnetotail, has thus been
envisioned as a reservoir of magnetic energy, which, through the concepts of a cross-tail electric field and frozen-in flux, would result in the release and subsequent transport of this energy to the auroral zone thereby causing the phenomena characteristic of a magnetospheric substorm. The term magnetospheric substorm was proposed by Coroniti et al., (1968) to emphasize the importance of the magnetosphere in auroral zone observations and to generalize the concept of the auroral substorm.

Magnetic bay activity in the nighttime auroral zone is observed to occur as the plasma sheet at 17 RE grows thinner (Hones et al., 1967), and at about the time of or following the peak of the magnetic bay the plasma sheet expands and contains plasma particles of higher energy. Hones et al., (1968) observed energetic electrons associated with auroral zone bay activity in the magnetotail at 17 RE approximately 15-30 minutes after the energetic electron precipitation began over the auroral zone. Hones stated that these observations are consistent with the idea that a magnetic bay occurs when plasma from the earthward part of the plasma sheet flows into the auroral zone tubes of force, that the plasma is energized there and that it is later ejected back into the tail allowing the relaxation of the bay. Vasyliunas, (1968), and Freeman and McGuire, (1967) have observed an inward motion of the inner edge of the plasma sheet in association with the development of bay activity.

Alfvén, (1939) predicted a forbidden region for particles traveling under the influence of a cross-tail electric field and the earth's dipole field. A region of net charge on the boundary of the forbidden region will tend to develop as this tail plasma is convected into the earth's dipole field. This region has been termed the Alfvén Layer (Schield, Freeman and Dessler, 1969) and coincides closely with the inner edge of the plasma sheet. The polar projection of the inner boundary of the plasma sheet observed by Vasyliunas, (1968),
Freeman and McGuire, (1967), and by Frank, (1967 c) has been shown to be coincident with the auroral oval (Schield, 1968). Thus a relationship between the plasma sheet and the auroral zone was established.

Once particles have been accelerated near the midnight meridian, regardless of what mechanism is doing the acceleration, they proceed to drift in longitude and latitude. The gradient drift is eastward for electrons and westward for protons (Roederer, 1967). These particles precipitate into the auroral zone as they move around the earth and either directly or indirectly are responsible for a large portion of the auroral phenomena.

On August 25-26, 1967, a particularly interesting magnetospheric substorm occurred. The substorm occurred during a period of little solar wind and magnetic activity. The substorm could be considered "classical" in a sense. Satellite and ground based records recorded very clean onset times of the storm features and a relatively quick recovery to prestorm conditions. The clean character of the substorm and the fortuitous positions of several satellites have permitted a detailed analysis of a classic substorm from its inception until its demise.
E. Magnetotail Coordinate System

In order to interpret these results and to study their relation to the magnetospheric substorm, it is essential that their spatial distribution be known as precisely as is possible. Due to the motion of the satellite as it travels the distant regions of the magnetotail and the motions of the magnetotail itself, (Speiser and Ness, 1967), it is often difficult to assign a particular spatial distribution to the observed particles. For example, the geomagnetic coordinates should reasonable well order the trapped particle distributions, since the energy density of the geomagnetic field is greater than the particle kinetic energy density and is the agent responsible for the trapping of particles. For radial distances, \( r > 25 \text{ RE} \), solar ecliptic coordinates should more accurately describe the spatial distribution of particles since it is the interaction with the solar wind which distorts the magnetosphere and forms the magnetotail. At all distances, particularly the intermediate range \( 12 \text{ RE} \leq r \leq 25 \text{ RE} \), the particle distribution would be best ordered by a combination of the two coordinate systems. For these reasons, Ness (1965) proposed a "solar magnetospheric" coordinate system which would incorporate features of both the geomagnetic and solar ecliptic coordinate systems.

In the solar magnetospheric (SM) coordinate system, the x-axis coincides with the earth-sun line and the X-Z plane includes the earth's magnetic axis. In this system the Y-axis is always normal to both the earth-sun line and the earth's magnetic dipole axis. The solar magnetospheric coordinate system thusly defined is illustrated in Figure 7. The dependence of this coordinate system upon the geomagnetic axis rather than the solar ecliptic plane emphasizes the importance of geomagnetic control of energetic particle distributions in the magnetotail as well as in the magnetosphere.
The Zsm-axis can be envisioned as a projection of the earth's magnetic dipole axis onto a plane perpendicular in the earth-sun line. During its daily rotation, the earth's magnetic dipole axis traces out a cone with a half-angle of \( \sim 11^\circ \) concentric about the earth's spin axis. The projection of this cone of revolution onto a plane perpendicular to Xsm then defines the angle over which Zsm varies with respect to the earth's spin axis in one rotation, i.e., \( \sim 22^\circ \). The Ysm-axis (solar magnetospheric equatorial plane) which is orthogonal to the Xsm-Zsm plane also tilts from +11\(^\circ\) to -11\(^\circ\) over one daily rotation. In addition to this "wobbling" of the solar magnetospheric equatorial plane due to the earth's rotation, the tilt of the earth's spin axis with respect to the earth-sun line changes as the earth revolves around the sun. Variations of the tilt of the solar magnetospheric equatorial plane with respect to the ecliptic plane are illustrated in Figure 8. The location of the neutral sheet lies closer to the solar magnetospheric equatorial plane around the times of the vernal and autumnal equinoxes since at these times the earth's spin axis is perpendicular to the earth-sun line.

By inspection of Figures 6 and 7 it becomes obvious that the neutral sheet does not normally lie exactly in the solar geomagnetic equatorial plane. It was pointed out by Ness (1965) that this deviation would be greatest at winter and summer solstice when the geomagnetic dipole deviates substantially from the Zsm axis. Murayama (1966) concluded that the deviation of the neutral sheet from the solar magnetospheric equatorial plane, \( \Delta \), must be larger with increasing \( \psi \), the geomagnetic latitude at the subsolar point. He approximated the deviation, \( \Delta \), by the relation

\[
\Delta = R_0 \sin \psi
\] (1)
where $R_0 = 8 R_E$ is a constant, independent of the distance from the earth and which was evaluated empirically. Bame et al., (1967) also observed a seasonal dependence of the plasma sheet orientation at $\sim 17 R_E$. They found that the plasma sheet at $17 R_E$ was $\sim 6^\circ$ above the geomagnetic equator in the fall and a similar distance below in the spring. During these two seasons the average separation of the solar magnetospheric and geomagnetic equatorial planes is $\sim 12^\circ$. They thus concluded that in these seasons the average position of the neutral sheet was about halfway between the two equatorial planes. Comparing this deviation $\Delta = 17 R_E \tan 6^\circ = 1.79 R_E$, with the approximation $\Delta = 8 R_E \sin 12^\circ = 1.66 R_E$, we see that the two results disagree by only 0.13 $R_E$. The tilt of the solar magnetospheric equatorial plane for the period of the August 25-26 substorm is shown in Figure 8.
F. Conclusions

In the following sections it will be shown that the energetic particle and plasma variations observed at 18 RE in the magnetotail are associated with the development of the nightside auroral substorm. Following the plasma "drop out" observed in the magnetotail, and coincident with the peak magnetic bay activity in the auroral zone, energetic electrons \( > 40 \text{ kev} \) appeared at 18 RE at flux levels 2 or 3 orders of magnitude higher than their poststorm levels.

During the initial phases of the plasma thinning, energetic electron flux anisotropies were observed at Vela 3A. It will be shown that if these anisotropic particle fluxes were due to field aligned currents and the auroral zone tubes of force extended to 18 RE in the tail, then approximately \( 10^6 \) amperes of electron current moved tailward during the initial plasma thinning.

It will also be demonstrated that plasma energized or injected into the neutral sheet at distances \( > 28 \text{ RE} \) and then transported earthward past the satellites with a drift velocity \( \vec{v}_d = \frac{\vec{E} \times \vec{B}}{B^2} \), provides an interpretation of the observed features of the initial development of the substorm.

The auroral substorm that started near midnight initiated a disturbance which propagated throughout the auroral zone. The disturbance pattern was measured on the noon and dusk meridians and at synchronous orbit. It will be shown that drifting particles accelerated near midnight, being confined to move in a geomagnetic field which exhibited adiabatic motions, provides a reasonably consistent interpretation of the auroral zone disturbance pattern observed on a global scale.
II. MAGNETOTAIL PLASMA AND PARTICLE VARIATIONS AND THE ASSOCIATED AURORAL SUBSTORM

A. Experimental Observations at 18 RE

During the geomagnetic substorm of August 25–26, 1967, the average radial distances of Vela satellites 3A and 4A were 17.7 RE and 18.2 RE respectively. Vela satellite 3A was at ~0200 local time and its average displacement above the estimated neutral sheet for the 3 hours of the substorm was 3.5 RE. Vela satellite 4A was closer to both the midnight meridian (~0100 local time) and the estimated position of the neutral sheet (DZ = -3 RE). The function DZ = -3 RE, indicates that Vela 4A was located three earth radii below the neutral sheet. The location of Vela satellites 3A and 4A with respect to the earth and the ATS-1 satellite is shown in Figure 9. For simplicity both Vela satellites trajectories have been plotted at a constant radial distance of 18 RE.

Figure 10 shows the energy density and average energy of electrons and protons in the 0.2 – 20 kev energy range observed by both Vela satellites at the time of the magnetospheric substorm. For comparison, the energy density and average energy of electrons observed by both satellites are plotted as a function of universal time. Also shown are the average energy and energy density of protons observed by 4A. In Figure 10 the radial distance, RE, the solar magnetospheric latitude and solar magnetospheric longitude, the tilt of the dipole axis toward the sun, and the distance from the estimated neutral sheet, DZ, is indicated every half hour for both satellites. The positive values indicated for the tilt of the magnetic dipole means that the tilt is toward the sun, which must be the case for the northern hemisphere in late summer. The distance from the neutral sheet, DZ, is calculated from the magnetospheric coordinates and the tilt of the magnetic dipole assuming the neutral sheet is
parallel to the solar magnetosphere equatorial plane and is "hinged" (Speiser and Ness, 1967), at the earth's magnetic equatorial plane at a geocentric distance of $10 \, R_E$ at the midnight meridian (see Figure 6).

In the discussion of the magnetotail plasma variations, the time 2200 UT, August 25, will arbitrarily be designated as the earliest that any possible sub-storm related activity was observed at $\sim 18 \, R_E$. Before 2200 UT the satellites were $6 \, R_E$ apart and were within the plasma sheet. The electron average energy ($\sim 1 \, \text{keV}$) and energy density ($\sim 15 \, \text{ev}-\text{cm}^{-3} \cdot \text{ster}^{-1}$) observed by 3A were consistently lower than the average density ($\sim 15 \, \text{keV}$) and energy density ($\sim 30 \, \text{ev}-\text{cm}^{-3} \cdot \text{ster}^{-1}$) observed at 4A. These facts tend to suggest that Vela 3A being $\geq 4 \, R_E$ above the neutral sheet is just inside the plasma sheet while Vela 4A, located less than $2 \, R_E$ below the neutral sheet, is well within the plasma sheet. This interpretation is further substantiated by the energetic particle distribution observed in the plasma sheet by Bame et al., (1967), Montgomery, (1968), and Murayama and Simpson, (1968). After the substorm the average electron energy and energy density in the 0.2 to 20 kev energy range are essentially the same at both satellites, which are by this time almost symmetrically located $3 \, R_E$ above and below the neutral sheet.

Assuming isotropic particle fluxes (Hones, 1967, 1968), the total plasma energy density in the plasma sheet before the substorm can be estimated as follows:

$$\rho_E \text{ (total)} = \rho_E \text{ (protons)} + \rho_E \text{ (electrons)} \quad (2)$$

$$\rho_E \text{ (total)} = (175 + 40) \, 4 \pi \, \text{ev} \cdot \text{cm}^{-3}$$

$$\rho_E \text{ (total)} = 2639.7 \, \text{ev} \cdot \text{cm}^{-3}$$

Equating this energy density to the magnetic energy density and solving for the magnetic field strength, $B$, gives:
\[
\frac{B^2}{2 \nu_0} = 2639.7 \text{ ev-cm}^{-3}
\]

\[
B = (2 \times 4 \pi \times 10^{-7} \times 2369.7 \times 1.6 \times 10^{-9} \times 10^{+6})^{\frac{1}{2}} = 3.25 \times 10^{-8} \text{ weber-m}^{-2}
\]

\[
B = 32.5 \gamma
\]

A magnetic field strength of this order of magnitude is characteristically observed at \(~17 \text{ RE}~\) in the plasma sheet (Heppner, 1965, Fairfield and Ness, 1967, Speiser and Ness, 1967, Fairfield, 1968, Behannon, 1968, Mihalov et al., 1968, Laird, 1969) and the magnetic and particle pressure balance has been verified (Lazarus et al., 1968). Another feature typically found in the plasma sheet is that the energy density and average energy of the protons is usually \(~3 - 5~\) time greater than the corresponding quantities for electrons. This implies that for equal number densities, the protons are moving \(~20~\) times slower than the electrons.

At \(~2204 \text{ UT}~\) the electron energy density at 3A started to decrease and eventually dropped below the threshold sensitivity of the electrostatic analyzer at \(~2325 \text{ UT}~\). The electron energy density of 4A did not start to decrease until \(~2243 \text{ UT}~\), or approximately 40 minutes after the decrease started at 3A. The electron energy density at 4A then recovered from a minimum of 2311 UT finally reaching its pre-event level at \(~2336 \text{ UT}~\). The minimum electron energy density at 3A could not be determined but it remained below the threshold sensitivity \((\sim 0.1 \text{ ev-cm}^{-3} \cdot \text{ster}^{-1})\) for about 17 min. The electron energy density at 3A started to increase at \(~2341 \text{ UT}~\) and was completely recovered by \(~2359 \text{ UT}~\). The return of the \(>50 \text{ kev}~\) electrons at \(~2346 \text{ UT}~\) as shown in Figure 11 is arbitrarily chosen as the time that 3A was given within the plasma sheet. The data shown in this figure were obtained from Vela 3A and 3B. Vela
3B was located outside of the magnetosphere and thus was conveniently located to observe solar x-ray events without the confusing presence of magnetospheric particles. Events seen at both satellites, such as the one at ~0020 UT, were attributed to solar x-rays and events which were seen only at 3A were probably caused by energetic particles. Thus the increase in electrons $>50$ kev seen only at 3A at ~2345 UT marks the entry of 3A into the plasma sheet. It is significant that the plasma leaves 3A before it leaves 4A; and returns to 4A before it returns to 3A. This is consistent with the picture of a thinning and then a thickening plasma sheet, since 4A was ~0.5 RE closer to the neutral sheet than was 3A.

After the plasma recovered at 3A and 4A it was observed to have an average energy of $\sim1.5-3.4$ kev, which is almost twice the prestorm value. Although the average energy observed by both satellites doubled, the post-storm energy density was the same or slightly less than its pre-storm value. If the average energy of the electrons increase while the energy density remains constant, the lower energy particles must be accelerated to higher energies and a spectral hardening would result. This "heating" of the plasma during the recovery of a magnetospheric substorm has important implications and will be discussed in the following section.
B. Development of the Night-Side Auroral Substorm

Figure 12 shows the electron energy density profiles at Vela 3A and 4A and the H-component of the Leirvogur and Sodankyla magnetograms. The first indication of magnetic activity occurred at Sodankyla at \( \sim 2200 \) UT. The H-component of the magnetic field started to slowly decrease and by \( \sim 2314 \) UT had been reduced by \( \sim 150 \gamma \). At 2314 UT the H-component decreased very sharply and by \( \sim 2326 \) UT had been further reduced by 330 \( \gamma \). The bay recovered quickly for the next 15 minutes when a second, but weaker bay started, reaching its peak at 0007 UT, August 26. Following this second bay the H-component had completely recovered by \( \sim 0116 \) UT. The H-component of the magnetic field at Leirvogur showed an increase of \( \sim 25 \gamma \) between 2200 UT and 2248 UT, and a subsequent decrease of \( \sim 25 \gamma \) by \( \sim 2318 \) UT. At this time the H-component dropped very precipitously for the next 3 or 4 minutes. The H-component of the magnetic field was reduced \( \sim 515 \gamma \) in this short period. After about 13 minutes of large amplitude fluctuations the bay at Leirvogur started a partial recovery which was terminated at 2342 UT by another sharp drop in H. This second bay reached its peak at 0000 UT, August 26, and had essentially recovered by \( \sim 0100 \) UT.

Freeman and Maquire, (1968), report a tendency for the plasma sheet to broaden out in local time as the storm grows in intensity. During relatively weak bay activity, similar to that observed on August 25-26, they observed a distribution of plasma at synchronous orbit which peaked sharply around local midnight. The features of the magnetic variations and ionospheric absorption observed in the night-side auroral zone, shown in Figure 14, are consistent with the picture of particle injection or acceleration over a narrow range in local time near midnight. The riometer and magnetometer data from the Japanese
station, Syowa, which is located in the Antarctic and is magnetically conju-
gate to Leirvogur is shown in Figure 15 with the Leirvogur magnetometer and
Reykjavik riometer data. The similarity of these data suggests that the initial
substorm or acceleration must have occurred in the vicinity of the equatorial
plane.

The close time association and nearly equal depressions in H indicate that
this substorm was broader in local time than was the initial slow disturbance
observed only at Sodankyla. This is also supported by the fact that at ~2320
UT Sodankyla was at ~0235 MLT and Leirvogur was located only ~5 degrees
west of the midnight meridian. Vela satellites 3A and 4A were at local times
0200 LT and 0120 LT respectively, and were positioned quite favorably in local
time with Sodankyla during this initial bay activity. It is also interesting to
note the similarity in the character of the slowly thinning plasma observed at
Vela 3A and the rather slow development in the bay at Sodankyla. The electron
average energy and energy density at both Vela 3A and 4A dropped abruptly
following this slow thinning as did the H component at both Sodankyla and
Leirvogur. The electron average energy and energy density started to slowly
recover at Vela 4A following the abrupt decrease at ~2243 UT. The recovery
was not observed at 3A, but presumably by this time 3A was no longer in the
plasma sheet. At ~2333 UT the electron average energy and energy density at
4A again dropped rather abruptly. Following this decrease in the plasma at 4A
both Leirvogur and Sodankyla had a second negative bay which followed a
partial recovery of the initial bay. This bay was much more pronounced at Leir-
vogur than it was at Sodankyla.

The temporal variation of energetic electrons observed at Vela 4A during
this substorm are shown in Figure 13. The differential energy channel (450 kev -
2.25 Mev) and the integral channel ( > 40 kev) are shown in this figure to
demonstrate the energetic electron behavior during this substorm. The > 40
kev electrons at 4A show a similar but more pronounced decrease than the
0.174 kev - 18.5 kev electrons did between 2200 UT and 2243 UT. The dis-
appearance of > 40 kev electrons at 2243 UT and again at 0012 UT indicates
that Vela 4A was near the lower edge or completely outside of the plasma
sheet. In Figure 10 it is seen that although the electrons in the 0.174 kev -
18.5 kev range decreases sharply at these times they do not completely dis-
appear at 4A. This implies that the more energetic particles are located closer
to the neutral sheet. Similar energy dependent particle distributions have been
implied by Bame et al., (1967), Montgomery, (1968), and Murayama and
C. Plasma and Energetic Particle Motions in the Magnetotail

The role of magnetic merging across the neutral sheet in accelerating electrons may be investigated in view of the present results. Dessler, (1968), has argued that magnetic merging across the neutral sheet of the geomagnetic tail will take place near the earth, (i.e., between about 10 and 30 RE). (See Figure 16.) Hones et al., (1967), as a result of energetic particle measurements at ~17 RE have argued that the merging, if it exists, must take place within 17 RE. Mihalov et al., (1968), observed the occurrence of both positive and negative Z components of the magnetic field in the neutral sheet at ~35 RE, and have suggested that merging must take place at distances of ~35 RE.

The fact that energetic electrons were seen at 18 RE after the associated bay activity seems to argue against the merging region being located further out in the tail than 18 RE. Due to the symmetry of the merging region, shown in Figure 17, the intensity of electrons flowing toward the earth and away from the earth should be comparable on each side of the neutral point. If the electrons were accelerated at the neutral line of the merging region and carried away from the merging region as depicted in Figure 17, then energetic plasma would be observed before as well as after the associated bay activity depending upon the location of the merging region. Bay associated enhancements of the energetic electron flux detected by Alouette (Jelly and Brice, 1967) and Injun 4 (Rao, 1968) in the midnight-dawn sector of the outer belt are generally 100 times more intense than the fluxes observed in these present measurements at ~18 RE. While it may be argued that these measurements are not necessarily related, due to the time difference of the observations or that the gross picture presented here cannot apply to an individual substorm, it is felt that the present evidence casts serious doubt on the concept of electron acceleration taking place in a field line merging region closer to the earth than 18 RE.
On the basis of the evidence presented here it is suggested that the acceleration of energetic electrons and protons occurs in the outer zone of the magnetosphere. The auroral substorm observed in the range of magnetic latitudes $\Lambda \approx 60^\circ$ to $\Lambda \approx 70^\circ$ further suggests that this acceleration occurs within auroral zone tubes of force, (Schield, 1968). That the substorm is observed in both auroral zones with strikingly similar features also implies that the acceleration occurred in the vicinity of the equatorial plane. The fact that energetic electrons were seen at $\sim 18 R_E$ following the peak in magnetic bay activity suggests that the tubes of force within which the acceleration took place did not extend to $\sim 18 R_E$ at the time of acceleration. Thus, the Vela satellites which were within a few earth radii of the estimated position of these neutral sheets, were on field lines which intersected the earth poleward of the auroral zone.

Since the data presented here clearly show that the plasma drop outs $\sim 18 R_E$ preceded by several minutes the bay activity observed in the auroral zone it would be interesting to investigate these temporal patterns in terms of possible plasma motions. The Leirvogur station and Vela 4A were chosen for this analysis because of their respective positions in local time. Figure 18 shows the energetic electrons observed at 4A and the horizontal component of the Leirvogur magnetogram. It is proposed that the variations in the $> 40$ kev electrons observed at $\sim 18 R_E$ could be indicative of plasma clouds being convected earthward in the $\mathbf{E} \times \mathbf{B}$ direction. The plasma clouds are then possibly accelerated on auroral zone tubes of force which intersect the earth near Leirvogur. During this acceleration some of the energized plasma escapes back out into the tail and is subsequently detected at Vela 4A. Figures 12 and 18 show that the first indication of a large scale plasma drop out at Vela 4A occurred at $\sim 2243$ UT. The sharp drop in H at Leirvogur occurred $\sim 35$ minutes later. In Figure 18 the time scale
of the > 40 kev electrons has been shifted 35 minutes to show the similarity in the two records.

The tubes of force which intersect the earth at Leirvogur cross the equatorial plane at \( \sim 6.06 R_E \). If the disturbance seen at Vela 4A and Leirvogur were caused by the same agent, then this agent must have traveled a distance.

\[
d = 18 R_E - 6 R_E = 12 R_E
\]

in \( \sim 35 \) minutes. This corresponds to an average velocity of

\[
V = \frac{d}{t} = \frac{12 R_E}{35 \text{ min}} = 36 \text{ Km-sec}^{-1}
\]

where 1 \( R_E \) = 1 earth radius = 6370 km. This velocity can be compared to the drift velocity of a particle within the neutral sheet.

The drift velocity of a particle in an electric and magnetic field is given by

\[
V_d = \frac{E \times B}{B^2}
\]

Assuming that the electric field \( E \) is in the plane of the neutral sheet and in the \( +Y_{SM} \) direction and that \( B \) is normal to \( E \) and directed in the \( +Z_{SM} \) direction; the drift velocity is determined by the relation

\[
V_d = \frac{E}{B}
\]

The value of \( B \) used in this calculation was 8.5 \( \gamma \), which is representative of the component of the magnetic field observed normal to the neutral sheet at \( \sim 10 \) to 20 \( R_E \) during magnetic storms (Laird, 1969). The value of \( E \) used was 0.3 mV/m, which has been postulated as the field required to form a forbidden zone for thermal particles that is approximately the size and shape of the plasmasphere (Kavanagh et al., 1968). With these values for \( E \) and \( B \), the drift velocity is calculated to be

\[
V_d = \frac{0.3}{8.5} = 35 \text{ km-sec}^{-1}
\]
This value is in excellent agreement with the previously determined drift velocity of 36 km-sec$^{-1}$. From Figure 18 it is apparent that the onset and recovery of the two bays at Leirvogur and the plasma drop outs at ~18 RE coincide quite closely when the time scale is moved 35 minutes. This fact together with the plasma drift velocity calculations tend to support the concept of plasma moving earthward prior to the auroral substorm.

The solar wind proton energy increased at 2212 UT from 900 ev to 1100 ev and eventually decreased back to 900 ev at 2354 UT (Hones private communication). The very close timing of this increase in solar wind pressure with the plasma drop outs and bay activity and the return of the plasma with the decrease in solar wind energy may be unrelated, but it is felt that this is consistent with the picture of the magnetospheric substorm presented earlier. If it is assumed that the plasma started earthward at 2212 UT then the origin of the plasma which passed Vela 4A and eventually arrived at the earth could be determined. Using the value of the velocity calculated previously and the difference in time of the solar wind increase (2212 UT) and the plasma drop out at 4A (2343 UT) the source region is estimated to be

$$r = vt = 35 \text{ km-sec}^{-1} \times 31 \text{ min.} = 10 \text{ RE}$$  (9)

further down the tail from Vela 4A. This puts the source region at

$$X_{Sm} = 18 \text{ RE} + 10 \text{ RE} = 28 \text{ RE}$$  (10)

from the earth and within the range of values quoted by Dessler, (1968) in which field line merging takes place.

The two drop outs in >40 kev electrons at Vela 4A each lasted for ~23 minutes. If these drop outs are associated with moving clouds of plasma starting at 28 RE in the tail, then the durations of these drop outs indicate that the plasma clouds were approximately 18 RE long and originally extended from the
position of Vela 4A (18 Re) to 28 Re. The almost complete recovery of the
> 40 kev electrons at ~ 2303 UT occurred about 15 minutes before the sharp
decrease in H at Leirvogur. This implies that if a plasma cloud did completely
pass Vela 4A before it reached a distance of 6 Re from the earth it must have
been less than 12 Re long. The second drop out and bay activity can be inter-
preted similarly.

The volume of tail emptied in this substorm can be calculated by comparing
the rate of energy dissipation in a typical bay event with the rate of energy loss
in the tail. Estimates of the energy dissipated in an auroral substorm made by
Axford (1965), Cole (1966), and Atkinson (1966) fall in the range of 10^{10} -
10^{11} watts. The rate of energy loss from the tail is

\[ \text{Tail loss rate} = \frac{\Delta U}{\Delta T} \cdot V \]  \hspace{1cm} (11)

The terms, \( \Delta U \) and \( \Delta T \), are the total particle energy density decrease observed
at Vela 4A and the duration of the plasma drop out. The minimum in electron
energy density occurred at ~ 2312 UT when it reached a value of ~ 1.6 ev-cm^{-3}
ster^{-1} \times 4 \pi \text{ ster} = 20 \text{ ev-cm}^{-3}. The proton energy density was not determined at
that time, but if a ratio of proton energy density to electron energy density of 4
is assumed then the total particle energy density at the peak of the plasma drop
out was ~ 100 ev-cm^{-3}. At the peak of the plasma drop out the energy density
had decreased by ~ 2400 ev-cm^{-3}, but since the peak was not broad it is assumed
for simplicity that the average energy density decrease for the 40 minutes of the
plasma drop out was ~ 2000 ev-cm^{-3}. The volume of the tail enveloped in this
calculation can be estimated by the compression of the plasma sheet observed by
both 3A and 4A. Vela 3A was ~ 3.5 Re above the neutral sheet and 4A was
~ 2.2 Re below at this time. Vela 3A was near the edge of the plasma sheet
when the initial compression started and eventually dropped completely out. At
the time of maximum compression 4A was outside or right on the lower edge of the plasma. These results suggest that the plasma sheet was compressed by approximately 1.3 $R_E$ on either side of the neutral sheet. Assuming that the plasma sheet is 40 $R_E$ wide at 17 $R_E$, the volume of plasma compressed into the neutral sheet is

$$V = 2.6 \times 40 \times 40 \times L$$

where $L$ is the length of compressed volume.

Equating the rate of energy loss in the tail to the median value for the rate of energy dissipation in an auroral substorm gives

$$5 \times 10^{10} \text{ watts} = \frac{2000}{40} \text{ ev-cm}^{-3}\text{-min}^{-1} \times 40 \times 2.6 \times L$$

Solving for $L$

$$L = \frac{5 \times 10^{10} \times 40 \times 60}{2000 \times 40 \times 2.6 \times 1.6 \times 10^{-19} \times 10^6 \times 40.57 \times 10^{12}} \text{ meters}$$

$$L = 8.888 \times 10^7 \text{ m} = 13.9 \text{ } R_E$$

Adding this distance to 18 $R_E$ it was found that the volume of particle energization extended to $\sim 32 \text{ } R_E$ in the magnetotail. The volume length estimated here is interpreted as an upper limit since not all of the plasma that was compressed probably did not enter the neutral sheet. It is perhaps notable that Mihalov et al., (1968), have reported that both negative and positive values of $B_{Zsm}$ occur with about equal probability in the transition region starting at $\sim 35 \text{ } R_E$. They have interpreted these results to mean that loops of field lines are crossing the neutral sheet, hence in their model of the magnetotail they postulate that the merging region is at $X_{sm} = -35 \text{ } R_E$.

All of these data seem to suggest that plasma or clouds of plasma are somehow injected into the vicinity of neutral point and move toward (and away from)
the earth at \( \sim 35 \text{ km/sec}^{-1} \). As the plasma moves toward the earth it depletes the ambient plasma somewhat and eventually reaches an auroral zone tube of force where it is energized. Some of the plasma is precipitated into the auroral zone, some drifts around the world in the equatorial plane, some goes into the formation of ring currents and a fraction of it is ejected back down in the tail. These speculations are subject to other interpretations and a detailed analysis of several similar events is required before any of these points be considered as absolute.

In addition to the bulk motions of the magnetotail plasma, anisotropies in energetic particle fluxes were detected during the initial plasma drop out at Vela 3A. Samples of the electron energy density (187 ev - 18 kev) taken with the analyzer looking toward the sun and away from the sun are shown in Figure 19. Electrons in the 187 ev to 18 kev range have velocities in excess of the Alfvén velocity in the tail and consequently any observed directionality in their intensity can be construed as indicative of a current. The current density in the sunward and anti-sunward directions were determined by the relation

\[
\mathbf{j} = ne\mathbf{v}
\]

(14)

where \( n \) is the electron number density, \( e \) is the electronic charge, and \( v \) is the rms electron velocity. The electron number density is given by

\[
n = \frac{\rho E}{\bar{E}}
\]

(15)

where \( \rho E \) is the electron energy density and \( \bar{E} \) is average electron energy. Both of these variables are determined from the data with the assumption that the particle anisotrophy is observed in 1 steradian. The rms velocity is obtained from the relation

\[
\frac{1}{2}mv^2 = \bar{E}
\]

(16)
where $E$ is the average electron energy. The difference in current densities toward and away from the earth indicates that during the initial plasma drop out a net electron current density of $\sim 15 \times 10^{-9}$ amp-m$^{-2}$ was flowing away from the earth. This current is shown in Figure 20 along with electron number density observed at Vela 4A and the negative magnetic bay at Leirvogur.

If these currents are assumed to be associated with the bay activity in the auroral zone, it would be interesting to calculate what total field aligned currents these anistrophies would produce. For the purpose of these calculations it will be assumed that the auroral zone tubes of force extended to $\sim 18R_E$, and that the auroral activity was spread over an area of $10 \text{ km} \times 1000 \text{ km}$. An investigation of the spread of auroral activity presented in the next section shows that the initial bay activity was spread over an area at least this large. Equating the magnetic flux in the auroral zone to the flux at $18R_E$ results in

$$\Phi_A = B_A A_A = B_T A_T = \Phi_T$$  \hspace{1cm} (17)

where $B_A$, $A_A$ are the field strength and area of auroral activity in the auroral zone and $B_T, A_T$ are the field strength and flux tube area at $18R_E$. Solving this equation for the cross sectional area of the auroral zone tube of force at $18R_E$ yields

$$A_T = \frac{B_A A_A}{B_T}$$  \hspace{1cm} (18)

The field strength at $18R_E$ is obtained by equating the magnetic field energy density to the total proton and electron energy density.

$$\frac{B^2}{2 \nu_e} = \frac{1}{2} \rho_e v_e^2 + \frac{1}{2} \rho_p v_p^2$$  \hspace{1cm} (19)

During the plasma drop out the total plasma energy density was $\sim 100$ ev-cm$^{-3}$ which gives a value of $6.34 \gamma$ for the tail field. Using the value $B_A = 5 \times 10^4 \gamma$, the auroral zone tube of force has an area of $\sim 10^{14}$ m$^2$ at $18R_E$. This area
together with a current density of $15 \times 10^{-9}$ amp/m$^2$ gives a total electron current of $\sim 1.5 \times 10^6$ amps flowing out the magnetotail during the bay activity at Leirvogur. This figure is comparable to that obtained by Cummings and Dessler, (1967) for field aligned currents interpreted as the source of transverse magnetic disturbances at 1100 km above the auroral zone. These calculations are presented here for their heuristic value and will not be investigated further in the description of the magnetospheric substorm.
III. DEVELOPMENT OF THE AURORAL SUBSTORM ON A GLOBAL SCALE

A. Method of Analysis

Preliminary investigations of auroral absorption by the cosmic noise technique, which was introduced by Shain, (1951), have been reported by Little and Leinbach, (1959), Reid and Collins, (1959) and Campbell and Leinbach, (1961). Using the results of an analysis of riometer data collected in Alaska over a 5 year period, Basler, (1963) described the temporal and spatial morphology of the aurorally associated ionospheric absorption of cosmic radio noise. More recently the riometer has been used to study auroral motions on a global scale (Hargreaves, 1967, 1968). The riometer is a good instrument with which to study gross motions of auroral disturbances. The riometer can be operated both day and night and is not affected by cloud cover or adverse weather conditions. The riometer responds to an area of ~100 km diameter at auroral altitudes and thusly is ideally suited for studying gross motions on a world wide basis. The riometer stations used in this study are indicated in Table 1 as well as their magnetic local times and invariant latitudes. The locations of the stations are shown in Figure 21 which is a polar plot using magnetic local time (MLT) and in invariant latitude (Λ) as coordinates.

Movements of the auroral disturbance were traced by using riometer data from three different areas of the northern auroral zone. The riometer records from Reykjavik, Iceland and Kiruna, Sweden were used to establish the initial source region of the disturbance. These stations were located very near the midnight meridian during the initial substorm activity. The Alaskan riometers were located ~12 hours in local magnetic time from the initial source of the disturbance and provided an excellent opportunity to investigate the features of the disturbance as it moved through local noon. Several Canadian riometers which were near dusk during this substorm detected both longitudinal and
latitudinal motions of the disturbance region. The Canadian and Alaskan riometer chains are separated by \(~ 6\) hours of local magnetic time and thus with the exception of the dawn meridian the movement of the disturbance was monitored in increments of \(~ 6\) hours local magnetic time.

By investigating the data from all of the stations the characteristic features of the event were categorized and recorded as a function of local magnetic time. The data from each station were analyzed to determine the first indication of any activity no matter how weak it was. The onset time, time of maximum and time of recovery of the larger more prominent events observed during this substorm were recorded and arranged in chronological order. Any other recurrent specific features were also cataloged, and the subsequent recovery to pre-storm absorption levels was determined when possible.

In analyzing the data thus obtained, two approaches were taken. In the first approach an attempt was made to associate the specific features in the major absorption event observed at each station. There was no activity prior to this substorm and the records from the various stations exhibit a similar character. In all of these records there appears to be one major absorption event. This major event observed at each station was preceded and followed in some cases by less intense activity, but not of sufficient magnitude to mask the temporal features of the prominent absorption event. It is felt that the features of the absorption at the various stations can be identified and that the quiet conditions, clean onset times and similarity in the events permits the motion of the disturbance region to be traced unambiguously. The second approach was to analyze the less intense events that were seen prior to the major increases in absorption. Even in the data obtained near midnight there were rumblings of increasing precipitation prior to the sudden onset in activity at \(~ 2315\) UT. The Canadian riometers indicated a disturbed absorption pattern between the time of the bay activity at midnight
and the appearance the more prominent event at ~0020 UT. The riometer data taken near local noon show rather featureless absorption events in Alaska. However, the data from the high altitude balloon situated over Ft. Yukon exhibited slowly increasing electron precipitation prior to a large and sudden onset of x-ray activity. The results of the analysis of the prominent absorption events will be presented in the next section. In the following section the less intense absorption events will be discussed, and finally, both events will be presented in a composite flow pattern in the auroral zone and in the equatorial plane.
B. Observation Near the Midnight Meridian

The riometer stations at Kiruna, Reykjavik and its magnetically conjugate station, Syowa, were located in the midnight sector during the initial phases of the auroral zone substorm. The conjugate pair, Reykjavik and Syowa, simultaneously observed a very sudden onset in ionospheric absorption at \( \sim 2316 \) UT. This was the first indication of any major activity in the auroral zone and followed the sudden plasma drop out at \( \sim 18 \) Re by \( \sim 35 \) minutes. The ionospheric absorption measured at Reykjavik and Syowa is depicted in Figure 22.

Although the Reykjavik riometer trace was off scale throughout most of this substorm, the major ionospheric absorption events at 2316 UT and 0000 UT are quite prominent and tend to exhibit features similar to events observed simultaneously at Syowa. The featureless character of the ionospheric absorption seen at Syowa prior to 2316 UT indicates that there was very little electron precipitation over this station before the auroral breakup. The horizontal component of the magnetic field measured at Leirvogur which is located close to Reykjavik and conjugate to Syowa also indicates only minor geomagnetic activity prior to \( \sim 2316 \) UT. These data are shown in Figure 23. The similarity in the features of the ionospheric absorption and geomagnetic variations at the conjugate stations suggests that the initial substorm activity took place in the vicinity of the equatorial plane.

The region of particle energization also encompassed the auroral zone tubes of force which intersected the earth at \( \sim 65^\circ \) in both hemispheres. At the time of the sharp increase in ionospheric absorption, both Reykjavik and Syowa were very near magnetic midnight and so were in a favorable position to observe the sudden increase in auroral activity which frequently occurs at this local time. The initial increase in ionospheric absorption seen at Syowa, although very sudden was only about 3.6 dB and would not be considered an extraordinarily
large or unusual absorption event. The Kiruna riometer and Sodankyla magnetometer stations are located approximately 45° in magnetic longitude to the east of Iceland and at the time of the onset of the intense auroral activity were at ~0230 MLT. The ionospheric absorption measured by the Kiruna riometer and the horizontal component of the geomagnetic field observed at Sodankyla are shown in Figure 24. The outstanding features of this absorption event are the very sudden onset time, easily determined in both hemispheres, and the striking similarity of the features of the entire event seen at magnetically conjugate points.

An examination of the Kiruna and Syowa riometer records shows that the sharp increase in ionospheric absorption observed at both stations did not occur simultaneously. The significance of the 2 - 3 minute delay in the onset of the event at Kiruna is questionable but is consistent with the idea that the source region of the auroral disturbance was located closer to midnight than Sweden (~0230 MLT). That this time difference is attributable to an equatorward motion of the source region is discarded in view of the fact that Reykjavik is ~3° poleward at Kiruna and equatorward motions of auroral activity during and following breakup are generally not observed. In fact, the character of the vertical component of the magnetic field variations observed at Leirvogur and Sodankyla shown in Figure 25 indicates that a westward electrojet moved poleward over both stations at ~2330 UT. The second ionospheric absorption peak seen in the Reykjavik and Syowa data at ~0000 UT was not observed at Kiruna. The ionospheric absorption did peak again at Kiruna but significantly later, i.e., at ~0030 UT. The difference in the character and temporal features of these events suggests that the auroral electrojet and hence the electron precipitation was north of Reykjavik at ~0000 UT and progressed equatorward after the bay activity which occurred at midnight universal time. The character of the magnetic
field components shown in Figure 25 implies that at \( \sim 0000 \) UT the auroral electrojet was located over Leirvogur and did not move southward over Sodankyla until sometime between 0000 UT and 0100 UT. The negative bays seen at both Sodankyla and Leirvogur at \( \sim 2315 \) UT are consistent with the concept of a poleward moving disturbance region during the initial bay and ionospheric absorption activity. The bay activity that occurred at \( \sim 0000 \) UT and which was much more pronounced at Leirvogur than at Sodankyla also suggests that the interpretation of a second auroral substorm starting at \( \Lambda \approx 66^\circ \) and then slowly progressing equatorward is correct.

Another interesting feature of the data presented here is the difference in ionospheric absorption and magnetic variations observed at Kiruna and Reykjavik prior to the large event which occurred at \( \sim 2315 \) UT. There was no detectable ionospheric absorption at either Reykjavik or Syowa prior to \( \sim 2315 \) UT and the Leirvogur and Syowa magnetograms show only minor disturbances before the sharp decrease in \( H \) at \( \sim 2316 \) UT. The horizontal component of the geomagnetic field observed at Sodankyla on the other hand, started to slowly decrease as early as \( \sim 2200 \) UT. The ionospheric absorption observed at Kiruna began to increase approximately 35 minutes before the intense absorption event at \( \sim 2318 \) UT. At the time of these observations Reykjavik was located approximately 22° in magnetic longitude before local midnight and Kiruna was located approximately 22° in magnetic longitude after midnight. These observations suggest that before the start of the auroral substorm of \( \sim 2315 \) UT there was increasing magnetic activity and particle precipitation in the midnight to dawn quadrant of the magnetosphere at \( \Lambda \approx 63^\circ \). It was shown in the previous section that these irregularities coincide with the plasma drop out observed at \( \sim 18 \) RE by Vela 3A and 4A.

An interpretation of the temporal and spatial morphology of the initial auroral zone disturbances can be made based on all of the data presented here. There
were apparently two auroral substorms occurring approximately 45 minutes
apart. During the first substorm, which occurred at ~ 2315 UT, the disturb-
ance which was initially observed at $\Lambda \approx 63^\circ$, moved poleward diminishing
in intensity as it moved. This initial disturbance region occurred very near
magnetic midnight and extended over at least 45$^\circ$ in magnetic longitude.
The second substorm started at ~0000 UT at $\Lambda \approx 66^\circ$, then slowly moved
equatorward diminishing in intensity. The active region associated with this
substorm was also located near magnetic midnight. All of the night side auroral
stations observed near pre-storm conditions at ~ 0100 UT.
C. Observations Near the Noon Meridian

Approximately 45 minutes after the first indication of ionospheric absorption in the night side auroral zone, riometers located in Alaska observed an increase in the day side auroral zone electron precipitation. The ionospheric absorption records of eight Alaskan riometer stations are shown in Figure 26. Seven of these stations are located within $10^\circ$ magnetic longitude and extend over a range in invariant latitude from $\Lambda \approx 71^\circ$ to $\Lambda \approx 59^\circ$. The eighth riometer station is at Kotzebue which is in western Alaska and approximately one hour earlier in magnetic local time than the other seven stations. At the time of the onset in the ionospheric absorption the central Alaskan riometer chain was very near magnetic local noon.

The most apparent feature in the Alaskan ionospheric absorption pattern is the latitudinal dependence of the intensity of the absorption. The most intense ionospheric absorption was observed at Paxton ($\Lambda \approx 63^\circ$). The intensity in the absorption decreases in magnitude monotonically with distance, both north and south of Paxton. The northernmost station is Bar I, Alaska ($\Lambda \approx 71^\circ$), observed virtually no increase in ionospheric absorption at any time during this auroral substorm and hence places a poleward limit on the dayside disturbed region. The low latitude extent of the disturbed region was very near $\Lambda = 59^\circ$ as is evident from the relatively weak absorption monitored by the Wildwood riometer. The peak absorption observed at local noon at an invariant latitude of $\Lambda \approx 63^\circ$ is consistent with the source region at midnight which encompassed the latitude range $\Lambda \approx 63^\circ$ to $\Lambda \approx 66^\circ$ presented in the previous section. From these data the extent of the disturbance at local noon appears to be almost entirely confined between $\Lambda \approx 60^\circ$ and $\Lambda \approx 70^\circ$ with a maximum located at $\Lambda \approx 63^\circ$. 

The data were then examined to determine if there were any systematic patterns in the motion of the disturbed region. The onset times of the ionospheric absorption events observed at each station were quite apparent and it is felt that they could be determined within an accuracy of 2 minutes or better. The onset times of the ionospheric absorption events observed at the Alaskan stations were not simultaneous and thus they indicated gross motions of the disturbance region. Ft. Yukon at an invariant latitude of $\Lambda \approx 66^\circ$ was the first station to measure enhanced ionospheric absorption. Within the next five minutes increased ionospheric absorption was detected at Kotzebue, ($\Lambda \approx 63^\circ$), Sheep Mountain ($\Lambda \approx 62^\circ$) and Paxton ($\Lambda \approx 63^\circ$). The event was not seen at Anchorage and Wildwood until $\sim 2336$ UT, which was $\sim 7$ minutes after it was first detected at Ft. Yukon. These results indicate that the disturbance region was observed first at $\Lambda \approx 66^\circ$ then proceeded to move $\sim 7^\circ$ south during the following 7 minutes, which would require a southward directed velocity component of $\sim 2$ km/sec. The equatorward motion of the disturbed region observed at local noon is depicted in Figure 27.

The effects of energetic electrons precipitating into the ionosphere over Ft. Yukon were also observed by a high altitude balloon borne x-ray detector. Flight 7 of Rice University's August 1967, arctic balloon expedition was launched at $\sim 0951$ UT on August 25.

The balloon was launched from Ft. Yukon and reached floating altitude at $\sim 1200$ UT, or 0200 local time. The winds aloft were very slight and thus the balloon was situated almost directly over Ft. Yukon for the entire duration of its flight. In fact, Flight 6, launched 6 days before was recovered $\sim 40$ km from Venetie, Alaska, which is 64 km northwest of Ft. Yukon. The balloon payload was a 4-channel x-ray detector sensitive to bremsstrahlung x-rays with energies $> 25$ kev, $> 50$ kev, $> 100$ kev, and $> 200$ kev. Due to an electronic
failure the > 200 kev channel did not perform properly during the flight. (See Pierson, 1968, for a more complete description of the instrumentation and a review of the entire flight series.) The electron precipitation over the balloon is related in a complicated way to x-ray fluxes (Anderson and Enemark, 1960) observed by the balloon payload. In the discussion which follows, references to electron precipitation will be based upon the character and magnitude of the observed x-ray fluxes in a general manner. The > 50 kev x-ray channel and the horizontal component of the geomagnetic field observed at College, Alaska for the duration of Flight 7 are shown in Figure 28.

From launch (0951 UT) until ~2330 UT the x-ray count rates in all of the energy channels were typical of the static cosmic ray background, with very little, if any, indication of enhanced activity. At ~2330 UT energetic electron precipitation started over the balloon and continued in an irregular fashion until 0214 UT. The count rates for the x-ray channels, obtained in this time interval are shown in Figure 29. The onset in enhanced electron precipitation seen at 2330 UT coincides with the start of the ionospheric absorption event detected by the Ft. Yukon riometer. The gross features of the x-ray activity observed by the high altitude balloon borne payload are similar to those of the ionospheric absorption event observed by the Ft. Yukon riometer. The similarity in the balloon data and the Ft. Yukon riometer data shown in Figure 30 suggests that the same causal mechanism was responsible for the perturbation observed at both locations.

A closer inspection of the x-ray event which started at ~0000 UT, revealed that well structured variations with widths of 5 to 10 seconds were superimposed upon the first large 6 - 10 minute pulsation. The fine structure of these 5 to 10 second pulsations are shown in Figure 31. A power spectral analysis of the data
for the time interval shown in Figure 31 revealed a strong 24 second periodicity. It is interesting to note at this point, without further interpretation, that the only characteristic electron or proton motion at \( L = 6 \) in the magnetosphere with this period is the bounce period of 100–200 kev protons with 30° pitch angles.

The observation of x-ray activity in more than one energy channel allows a determination of the spectral characteristics of the primary electrons to be made. From an inspection of the x-ray data shown in Figure 29 it is apparent that the peak x-ray flux in the \( \geq 25 \) kev channel decreased from the first event to the second, and the \( \geq 100 \) kev x-ray peak flux increased. To demonstrate the spectral hardening of the x-rays during these events, the ratio of counts in the \( \geq 100 \) kev channel to the counts in the \( \geq 25 \) kev channel is shown in Figure 32.
D. Observations Near the Dusk Meridian

Large and well defined auroral absorption was next observed to occur over Canada. Riometer records for four Canadian stations conveniently spaced in latitude and one Antarctic station are shown in Figure 33. The positions of the Antarctic stations, South Pole and Byrd, are shown in Figure 21 at their conjugate points in the northern hemisphere. The conjugate stations, Great Whale River and Byrd, had several riometers in operation at the time of this event. Each station had an array of 5 riometers which monitored the absorption to the north, south, east, west, and vertically. The data from these two stations are shown in Figure 34 and Figure 35. The disturbance region did not move as far poleward as South Pole (\(\Lambda \approx 75^\circ\)) and was barely discernable at Churchill (\(\Lambda \approx 70^\circ\)). Ottawa (\(\Lambda \approx 58^\circ\)) indicated only minor activity and hence placed a low latitude boundary on the disturbance region. The disturbance region was confined to a spread in latitude of from \(\Lambda \approx 60^\circ\) to \(\Lambda \approx 70^\circ\) as it passed over Canada, and therefore the latitudinal extent of this region is comparable to the region of activity observed in Alaska.

The motion of the disturbance region in Canada was determined primarily by investigating the Byrd and Great Whale River records. Due to the multiplicity of viewing directions at each station it was possible to detect latitudinal and longitudinal motions of the disturbance region and to observe the motions in both auroral zones. It is apparent in both sets of data that there were some indications of activity as early as \(\sim 2316\) UT. The time of these initial departures from the quiet day values coincides with the very sharp in the horizontal component of the magnetic field and the sudden increase in absorption observed near midnight. For the next hour the rumblings of the some weak activity were apparent at both Byrd and Great Whale River. These manifestations are particularly evident in the data from the northward looking riometer at Byrd, and the southern
looking riometer at Great Whale River. It is felt that the disturbance respon-
ible for these small absorption events must have been located equatorward of
both stations, at least during the early parts of the storm associated activity
observed in Canada.

Looking at the prominent absorption event that occurred between 0000 UT
and 0030 UT at all stations, it is possible to detect both latitudinal and longi-
tudinal motions of the disturbance region. At Great Whale River (Λ ≈ 68°)
the event was detected to the south at ~0016 UT, then overhead at ~0018 UT
and finally to the north approximately ~0026 UT. This poleward motion was
also detected at Byrd. It should be remembered when inspecting the Byrd data
in Figure 35, that a poleward expansion would be seen first to the north, then
overhead and finally to the south since Byrd is in the southern hemisphere.

In all of the Canadian and Antarctic data the prominent absorption peak
is generally quite sharp and relatively weak. This is in contrast to the much
broader and smoother absorption events observed at the Alaskan sites, and any
unifying interpretation of these events must be able to explain these differences.
E. Global Movement Pattern of the Auroral Zone Disturbance

From the time sequence of events it is apparent that the sharp absorption event started near magnetic midnight and propagated eastward around the auroral zone. The disturbance which started sharply at $\sim 2315$ UT in the midnight sector appeared $\sim 45$ minutes later at the Alaskan stations. The disturbance proceeded eastward and arrived over Canada $\sim 15$ to 20 minutes after it passed Alaska. Since Alaska is $\sim 180^\circ$ in magnetic longitude from the source of the disturbance, the observed time delay of 45 minutes corresponds to an eastward movement of $\sim 4^\circ$/min. If a constant propagation velocity of $4^\circ$/min. is assumed around the entire auroral zone it becomes possible to project the motion of this eastward moving disturbance into a magnetic polar plot. Figure 36 shows the progression of the peak absorption activity projected onto a magnetic local time, invariant latitude plot. The wave fronts in this figure are drawn at 10-min. intervals.

Figure 36 accurately depicts the motion of the disturbance region around the auroral zone for the magnetospheric substorm of August 25-26. The southward motion of the absorption event observed in Alaska is interpreted as resulting from an adiabatic expansion of the magnetosphere and the subsequent equatorward motion of the disturbance region. The poleward motion of the northern boundary of the disturbed region that occurred in Alaska at $\sim 0100$ UT and the observed poleward motion in Canada at $\sim 0018$ UT both occurred during adiabatic magnetospheric compressions. The 15 to 20 minute delay in the peak of the absorption event between Canada and Alaska is explained quite well by a $4^\circ$/min. eastward propagating disturbance.

While the prominent absorption peaks fit well into the scheme of an eastward drifting disturbance, the less intense and earlier absorption events observed in Canada do not. It is particularly evident that there were significant
absorption events seen in the Ottawa, Byrd, Great Whale River, and Moosonee records prior to the arrival of the eastward propagating disturbance. These disturbances occurred \(~15\) to \(30\) minutes after the initial activity observed near midnight. Due to the relatively weak absorption, produced by this disturbance it was not possible to determine the motion of the disturbance region with any certainty. The short period of time (\(~15\) minutes) between the midnight activity and the first indications of absorption observed over Canada would require an abnormally high eastward drift velocity (\(~20^\circ/min\)) if these disturbances are attributed electrons. For this reason these initial events are assumed to be associated with a westward propagating disturbance. A magnetic polar plot of the westward moving absorption events is shown in Figure 37. A constant velocity of \(4^\circ/min\). is assumed in making the \(10\)-min. time contours. Although the data used in making this plot are sparse it is felt the interpretation implied therein is consistent with the observations.

The eastward and westward motions presented here are projected on a single polar plot producing the composite flow pattern shown in Figure 38. All wavefronts drawn in Figure 38 are at \(10\)-min. intervals. Since there are no data available from the dawn region of the auroral zone the westward motion is terminated in Alaska. Thus, Figure 38 depicts most of the features of the auroral substorm observed on a global scale.

In order to investigate the relationship of the auroral substorm with related events occurring in the equatorial plane, the composite picture of the features of the polar substorm projected onto the equatorial plane are shown in Figure 39. The equatorial projection used here was taken from Schield, (1968) and the positions of the auroral zone stations are indicated by the symbols. As was pointed out previously, the choice of the equatorial plane seems justified in view of the close similarity in the character of events observed at conjugate stations.
Figure 39 shows the initial acceleration point to be at $L = 6$ on the midnight meridian. From the arguments presented in the first section it is felt that the source of the energetic particles must have been located very near this vicinity. It cannot be concluded, on the observations made at two observatories at approximately the same latitude, that this choice of a source region is the only one possible for this substorm. However, a source located at this point appears to be consistent with the observations in this particular case. From this source the disturbance moves eastward and westward arriving concurrently at noon. The westward moving disturbance is depicted as having a larger spread in the initial absorption events observed in Canada. A velocity of 4.9 min.

$$V_d = \frac{2R \cos \lambda}{\tau} = 3 \frac{\text{km}}{\text{sec}},$$

in the auroral zone indicates a corresponding velocity in the equatorial plane of $\sim 45$ km/sec. The poleward expansion seen in the auroral zone at $\sim 0015$ UT, is seen as a movement away from the earth in the equatorial plane. It is interesting to note that the eastward moving disturbance was not observed at distances less than $4R_E$ in the equatorial plane. The westward moving disturbance appeared to penetrate closer to the earth than $4R_E$ in the midnight-dusk quadrant. Asymmetric distributions of low energy protons have been postulated to provide partial ring currents (Cummings, 1966, Cahill, 1966) which are usually centered about 1800 local time. These partial ring currents have also been proposed as a possible source of the low-altitude daily-disturbance variations. Figure 40 shows that there were low-altitude daily-disturbance variations at the time of the auroral substorm. In fact, all of these stations represented in this figure show a definite decrease in the horizontal component of the geomagnetic field at $\sim 2315$ UT. The $H$ component decreased even further and eventually recovered at about the end of the polar substorm. The data tend to suggest that there were westward moving protons around $\sim 1800$ local time at low $L$-values.
F. ATS Satellite Observations

The features of this substorm were also observed at synchronous orbit (6.6 $R_E$), and on approximately the same magnetic meridian as Ft. Yukon. The position of ATS-1 during the period of this substorm has permitted the motion of energetic electrons in the equatorial plane to be investigated in relation to the auroral zone perturbations observed at local noon. The ATS-1 satellite was launched on December 6, 1966 into a stationary orbit at a geocentric distance of 6.6 $R_E$. The satellite is stationed at 150$^\circ$W, 0$^\circ$N and the base of the magnetic field lines which passes this equatorial vicinity is indicated in Figure 21.

One of the experiment aboard ATS-1 is a six-element solid-state detector telescope oriented perpendicular to the spin axis of the satellite. This instrument was built by the Bell Telephone Laboratory and was discussed in detail by (Lanzerotti, 1968). The $E_e > 0.4$ Mev and $E_e > 1.1$ Mev electron fluxes seen at ATS-1 for August 25-26, 1967 are shown in Figure 41 along with the planetary index $k_p$. From 0900 UT, August 25, until the time of the large non adiabatic increase at 2324 UT, the $> 0.4$ Mev and 1.1 Mev electron fluxes were considerably lower than their normal quiet day values depicted by the dashed lines in Figure 41. This suggests that the magnetosphere was in an expanded condition as a result of a low rate of solar wind momentum interchange at the magnetopause. This conclusion is also supported by the ATS-1 magnetometer data shown in Figure 42. The magnetic field data show very little magnetic agitation, and the magnitude of the horizontal component was 10 $^\gamma$ to 20 $^\gamma$ below its normal level.

The first indication of energetic electrons detected by ATS-1 during the auroral substorm was at $\sim$ 2323 UT or approximately seven minutes after the onset of the magnetospheric substorm on the night side of the earth. The sudden increase in energetic electrons seen by the BTL instrument is shown in Figure 43.
The sharp spike in energetic electrons is evident in the $E_e > 400$, $> 600$, $> 800$, and $> 1100$ keV channels. There are variations in the higher energy channels but they are not significantly disturbed to provide a means of analysis. The amplitude of the spike decreases with increasing energy and the signal in the higher energy channels may even be depressed at the time of this spike. In the four lowest energy channels it is apparent that there is a recurrent increase in electrons. The fact that the ATS-1 magnetometer indicated very little field variations during this event implies that these flux changes were non adiabatic in character. Adiabatic fluctuations are seen in Figure 43 at ~ 2330 UT, 0010 UT, 0040 UT, and 0100 UT.

The horizontal component of the magnetic field continued to decrease an additional 10 $\gamma$ and by ~ 0012 UT had reached a minimum value of 100 $\gamma$. The horizontal component of the magnetic field then began an erratic recovery and at ~ 0014 UT increased to a level of ~ 120 $\gamma$ which is approximately the same as its prestorm level. The reduced field intensity during the period of time in which the energetic electron increases were observed indicates that the variations in electron flux were non adiabatic. If these electron spikes were non adiabatic then they must have been locally accelerated or accelerated within the magnetosphere and drifted in longitude eventually reaching the ATS-1 satellite.

To locate the source of these electrons the features of the electron spike were examined to determine if there was any dispersion in their arrival times. The time of any significant departure of the electron count rate for each channel was noted. This departure was generally positive (increased count rate) for the lower energy channels and negative (reduced count rates) for the higher energy channels. Assuming that the acceleration occurred at time $t_0$, the distance to the source region, $d$, is given by
\[ d = V_d(E) \left( t(E) - t_o \right) \]  

(20)

The drift velocity \( V_d(E) \) used in these calculations was the mean drift velocity for electrons near local noon and near local midnight as given by Roederer, (1967). The time \( t(E) \) was the time of the onset of electrons or variations in electron count rate observed for each energy channel. Arranging this equation into the slope-intercept form of a straight line gives

\[ V_d(E) + (E) = V_d(E)t_o + d \]

(21)

where the time of acceleration, \( t_o \), is the slope and the distance to the source region, \( d \), is the intercept. If all of the particles were accelerated simultaneously and at the same location then a plot of \( V_d(E) + (E) \) should be a straight line with slope, \( t_o \), and intercept, \( d \). Thus the time and the point of acceleration could be determined by such a parametric study. Figure 44 shows the results of this analysis. Included in this analysis are the onset times for the \( > 25 \) kev and \( > 100 \) kev balloon x-ray data. It is apparent that no single line can be drawn through these points and consequently it is felt that not all of the particles had a common origin.

To explain these results it becomes necessary to postulate three source regions as indicated by the three straight lines drawn through the data points. The two points defining the balloon data indicate that the increases in precipitating electrons must have originated or were accelerated very close to the position of the ATS-1 satellite. The intermediate energy range (0.100 - 1.1 Mev) electrons have an intercept of a 27\(^{\circ}\) longitude further west indicating that these particles were accelerated near local noon. The more energetic electrons (\( E_e > 1.1 \) Mev) were accelerated \( \sim 146^{\circ} \) west of ATS-1 or at \( \sim 0330 \) LT. These various locations are shown in Figure 45. Such an energy dependent spread in
acceleration regions is difficult to explain and furthermore, not all of the data used in this approach corresponded to increases in energetic electrons.

A more stringent criteria was then used in determining the onset time of energetic electrons. The time of half maximum of the electron spikes in the three lowest energy channels was then employed in a similar analysis and the results are shown in Figure 46. The interpretation of these data is that if the energetic electrons observed in these energy channels were accelerated and then drifted to the vicinity of the ATS-1 satellite, then they must have originated $\sim 30^\circ$ to the west. The line in Figure 46 is drawn through the points derived for this analysis on the basis that there was no electric field across the magnetosphere. The inclusion of an electric field did not alter the drift periods of these energetic particles considerably. The drift velocity of a 0.4 Mev electron increased from 0.239$^\circ$/sec to 0.272$^\circ$/sec as the electric field across the magnetosphere was changed from 0 to 180 kv.

The lack in dispersion in the onset time of the initial electron spikes is confusing, in that it is felt, at least intuitively, that the acceleration of these particles took place near midnight. Through the kindness of L. J. Lanzerotti of the Bell Telephone Laboratory additional data on similar events were provided for analysis. The interpretation of these events will be discussed by him in a forthcoming publication and so only the more interesting features will be outlined here. An event which occurred near midnight on April 2, 1967 is shown in Figure 47. Another event which occurred near dawn on March 18, 1967 is shown in Figure 48.

From an inspection of Figures 42, 47, and 48, several features of these events tend to follow a consistent pattern:

a. The initial onset times for the various energy channels show an increasing dispersion in local time.
b. The widths of the initial spikes and the second electron increases tend to broaden in local time.

c. The fine structure in the electron spikes near midnight become "washed out" in local time.

These remarks are illustrated in Figure 49. The dispersion in widths and onset times of the electron spikes observed in these events indicate that these events are accelerated near midnight and that they tend to "smear out" as they drift in longitude. The acceleration does not occur simultaneously for all energy particle or does not occur over the same regions of the magnetosphere. It is entirely possible that the acceleration mechanism of energetic electrons is both energy dependent and takes place over large regions of the magnetosphere.

The fact that the second electron increases seen in all of these data exhibit large time dispersions in their onset time, even for the midnight event, suggests that these increases are not independent events but are perhaps the return of the electrons in the first spike. If the second increases are a return of the initial spikes then the time between their peaks should be the drift period for that energy electrons. The time between subsequent peaks for all the data in these three events is plotted in Figure 50 as a function of the energy of each channel. The Hones-Roederer drift period is also plotted as a function of energy in this figure. Although the fit is not perfect there can be little doubt that the second peak is the return of the first spike after drifting through one revolution around the magnetosphere. This fact substantiates the earlier conclusion that the initial energization of particles take place within the magnetosphere and in these cases, on closed drift shells.

The data obtained by the ATS-1 satellite tend to support the contention that electrons were accelerated near midnight, drifted eastward and were seen in the
equatorial plane near local noon. These electrons were accelerated within the magnetosphere as evidenced by the fact that they are seen to occur on closed L shells and are able to completely circumvent the earth. Exactly where, and how, these energetic particles are energized is beyond the scope of this thesis but they are important events in themselves and certainly warrant further investigation.
IV. SUMMARY AND CONCLUSION

The emphasis of research in space science is slowly shifting from a phenomenological description of our environment to a study of the physical processes that occur within this environment. Although experimental data are essential to research, it must be accompanied by theoretical consideration. From these considerations, the relation and correlation of the various physical phenomena are examined and a model of our environment evolves. The validity of any model is determined by its ability to organize the data, old and new, and to provide guidelines for future research. In some areas of research there are often several models which are proportioned to explain the observed phenomena. This is particularly true in the areas of magnetospheric and auroral research. Despite the many auroral and magnetospheric theories, several basic features of the magnetospheric substorm are still unexplained. Such basic questions as; How does the solar wind couple with the magnetosphere?; What role does the magnetotail play in auroral processes?; How is energy transported between different regions? have not yet been answered.

It is generally accepted that the ultimate source of energy, which drives the magnetospheric substorm, is the solar wind. One theory suggests that the solar wind drives a convection current of plasma in the magnetotail and outer radiation zone. The convection of this plasma results in unstable conditions which, when released, accelerates the particles and generates hydromagnetic waves. These particles and hydromagnetic waves then move on a global scale manifesting themselves in a variety of forms. These perturbations, taken collectively, have been given the name, magnetospheric substorm. It is within this general framework that the phenomena associated with the magnetospheric substorm of August 25-26 have been interpreted.
The first indication of any storm associated activity was observed at $\sim 18 \text{ RE}$ in the magnetotail. Large scale energetic particle and plasma variations were observed by two Vela satellites simultaneously. At the start of the magnetotail irregularities, the satellites were $\sim 6 \text{ RE}$ apart and both were within the plasma sheet. Prior to the commencement of the magnetotail activity, both satellites were measuring electron and proton fluxes and spectra characteristic seen at these locations. Vela 3A was further from the predicted position of the neutral sheet than Vela 4A, and was the first satellite to measure a plasma "drop out". The plasma continued to be compressed until it was $\sim 4 \text{ RE}$ thick. At this time, Vela 4A was either outside, or just at the lower boundary of the plasma sheet. The plasma sheet then expanded enveloping 4A and eventually 3A. Although Vela 3A was closer to the earth than 4A, the plasma was observed to leave 3A first and to return to 3A last. This is consistent with the picture of a thinning and then an expanding plasma sheet. Following the plasma "drop out" observed at both satellites, energetic electrons $> 40 \text{ keV}$ appeared at $\sim 18 \text{ RE}$ in the magnetotail at flux levels 2 or 3 orders of magnitude higher than their post storms levels. Factor of 3 increases were observed in the 450 keV to 2.25 MeV energy range. During the initial phases of the plasma thinning, energetic electron flux anisotropies were observed at 3A. These anisotropies indicated that roughly ten times as many electrons were moving away from the earth as were moving toward it. Whether these anisotropies resulted from a field aligned current system, energetic electron pitch angle distribution, or some other phenomena is not known. It was speculated that if these anisotropic particle fluxes were due to field aligned currents and the auroral zone tubes of force extended to $\sim 18 \text{ RE}$ in the tail, then approximately $1.5 \times 10^6$ amperes of electron current moved tailward during the initial phase of the plasma thinning.
The similarity in the features of the night side auroral zone ionospheric absorption and magnetometer data, and the energetic electron characteristics observed in the magnetotail suggests that the magnetotail plays an active role in the auroral substorm. The auroral disturbances were observed to follow the plasma variations at \( \sim 18 \, R_E \) by several minutes. The concept of a plasma cloud moving earthward past the satellites with a drift velocity given by

\[
\vec{V}_d = \frac{\vec{E} \times \vec{B}}{B^2},
\]

was introduced as a possible explanation of the features observed in the tail and near the midnight auroral zone. It was also suggested that this plasma was energized or injected into the neutral sheet at distances \( \geq 28 \) earth radii from the earth. This plasma cloud was then transported toward the earth by the action of a cross-tail electric field. The acceleration of the energetic electrons and protons is thought to have occurred in the outer zone of the magnetosphere on tubes of flux which intersect the earth's surface at auroral latitudes. This acceleration probably takes place in the vicinity of the equatorial plane due to the similar character of the ionospheric absorption and magnetic variations observed simultaneously in both auroral zones. The fact that energetic electrons were seen at \( 18 \, R_E \) after the peak in auroral zone magnetic bay activity indicates that the tubes of force within which the acceleration took place, did not extend to \( 18 \, R_E \) at the time of acceleration. The bursts of energetic electrons observed at \( 18 \, R_E \) following the bay activity could be explained by an expansion into the tail of the auroral zone tubes of force carried by plasma heated in the acceleration process.

The initial disturbance associated with the auroral substorm took place at a distance of \( \sim 6 \, R_E \) in the equatorial plane and very near the magnetic midnight meridian. This acceleration injected energetic particles into the magnetosphere. Once the particles were accelerated they proceeded to drift in longitude,
electrons to the east, protons to the west. A fraction of the more energetic electrons escaped back out into the tail eventually passing Vela 3A and 4A and causing enhanced count rates in the high energy electron detectors. The electrons and protons that were drifting around the world in the equatorial plane were gradually scattered into the loss cone, or were perturbing the ambient electron population in such a way as to cause electrons to be precipitated into the auroral zone.

Approximately 45 minutes after the substorm started near the midnight meridian, riometers located near local noon indicated increased ionospheric absorption. The perturbed region observed at local noon displayed an equatorward motion of ~2 km/sec and was confined to a range of latitudes between \( \Lambda = 60^\circ \) and \( \Lambda = 70^\circ \) with maximum absorption occurring at \( \Lambda = 63^\circ \).

The prominent absorption peaks in the Canadian data were observed to occur approximately 17 minutes after the peak electron precipitation detected by the balloon over Ft. Yukon. As the disturbance passed over Canada it was observed to exhibit a rapid poleward motion in both hemispheres and was confined to approximately the same latitude range as the Alaskan disturbance. Smaller and less intense ionospheric absorption detected prior to the large and well developed event was also detected by the low latitude Canadian stations.

The concept of drifting electrons, accelerated near magnetic midnight, being confined to move in a geomagnetic field which exhibited large scale motions, is felt to best explain the features of the auroral disturbances pattern observed around the world. The weaker and less dramatic absorption activity detected near the dusk meridian prior to the prominent absorption peak is interpreted as a manifestation of a westward moving disturbance. Since the disturbance moved with a velocity comparable to the eastward moving electrons, and the low
latitude magnetic observatories in the noon-dusk sector were measuring disturbance daily variations normally associated with partial ring currents, it is suggested that their features are best described by postulating westward moving protons. The simultaneous arrival at local-noon of drifting electrons and protons would also explain the broad, structureless ionospheric absorption events measured by the Alaskan riometers. The motion of these disturbance patterns projected onto the equatorial plane show an initial acceleration or injection which occurred on the midnight meridian at \( \sim 6.6 \, \text{RE} \) radial distance. The disturbance then propagated eastward and westward with a velocity of \( \sim 45 \, \text{km-sec}^{-1} \). The eastward moving disturbance did not penetrate closer to the earth than \( 4 \, \text{RE} \) while the westward moving disturbance was observed at equatorial distances of \( \sim 3.5 \, \text{RE} \).

The magnetic field and energetic electron measurements made at synchronous orbit support the contention of drifting electrons and large scale magnetospheric motions. Conditions returned to pre-storm levels within the auroral zone at synchronous orbit and is the magnetotail nearly 2 hours after the start of this magnetospheric substorm.

Although the features of the data presented here can be interpreted in a generally consistent manner within the framework of the magnetospheric model discussed earlier, there are several outstanding problems which are still unanswered. It is possible that continued analysis of the data presented here may answer some of these questions and that additional data on the magnetospheric substorm of August 25-26, 1967 would certainly contribute substantially to this effort. However, as was pointed out in the introduction, any model based on an analysis of one substorm is subject to multiple interpretations, and hence it is felt that most of the questions raised in this analysis would best be approached by a statistical analysis of several similar substorms.
ACKNOWLEDGEMENTS

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### Table 1

\[
\frac{1}{\sqrt{1 - \cos^2(\theta)}} = \text{MTL (1200 UT)}
\]

Station
REFERENCES


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FIGURE CAPTIONS

Figure 1. Comparison of the auroral oval and various high latitude boundaries versus local magnetic time (McDiarmid and Burrows, 1967).

Figure 2. Location of the auroral oval as a function of the local auroral zone magnetic index Q (after Feldstein and Starkov, 1967).

Figure 3. Representation of the solar wind interaction with the geomagnetic field in the noon-midnight meridian plane (from Ness, 1966 taken from Anderson, 1966). The radiation belts are shown as consisting of a stable trapping zone confined within field lines of up to approximately $70^\circ \pm 5^\circ$ latitude although a strong day-night asymmetry exists. In addition, a particle tail or cusp region is defined on the night side of the earth as well as the plasma and neutral sheets.

Figure 4. Magnetospheric model in which magnetic merging is negligible (after Dessler, 1964; and Dessler and O'Brien, 1965).

Figure 5. Magnetospheric models that envelope appreciable magnetic merging.

a. Magnetosphere proposed by Dungey (1961, 1962, 1963). The arrows indicate plasma flow. Although not shown explicitly, the magnetic field lines from the polar caps connect directly to the interplanetary magnetic field.

b. A more detailed drawing of Dungey's magnetosphere by Levy et al., (1964) showing the direct connection of field lines coming out of the polar caps. Note that beyond the
neutral line at the back of the magnetosphere, the field tends to return to interplanetary conditions as indicated by field line 8".

**Figure 6.** Schematic drawing of the overall distribution of high-energy electrons in the magnetospheric tail based upon experimental evidence so far available. (From Murayama and Simpson, 1968, taken in large part from Figure 5 by Speiser and Ness, 1967).

**Figure 7.** Definition of the solar magnetospheric coordinate system used in interpretation of the position of the neutral sheet as observed in the magnetic tail of the earth.

**Figure 8.** Illustration of the variation of the tilt of the equatorial plane of the solar magnetospheric coordinate system with respect to the ecliptic plane. Superimposed is the time of Rice University's balloon flight number 7, and the August 25-26, 1967 magnetospheric substorm.

**Figure 9.** Oblique view of the magnetosphere illustrating the relative positions of Vela satellites 3A and 4A and the ATS-1 satellite at the time of the magnetospheric substorm.

**Figure 10.** Electron and proton energy density and average energy measured on August 25-26, 1967, by Vela satellites 3A and 4A. The solar magnetospheric latitude and longitude (degrees) and the distance, \(Z\) (earth radii) from the estimated plane of the neutral sheet are given for each satellite. The tilt of the earth's dipole axis (degrees) is also shown. Positive tilt means the earth's magnetic axis is inclined toward the sun. The data shown in
this Figure were obtained in the anti-sunward direction. The discontinuity and arrows in the 3A data indicates count rates below the anti-sunward sensitive threshold of ~ 0 to 1 counts and suggests that 3A was not in the plasma sheet at these times. (The positional coordinates of the Vela satellites will not be given on any of the following Figures.)

**Figure 11.** X-ray fluxes measured on August 25-26, 1967, by Vela satellites 3B and 3A. Vela 3B was outside the magnetosphere at the time of these measurements and a comparison of the 3B and 3A data allows the spurious solar x-ray bursts observed in this tail to be recognized. The B(+) data are the same as D(x) and C, but are recorded on a more sensitive scale. The return of the plasma to 3A was observed at 2346 UT. The large bursts of solar x-rays seen at ~ 0025 UT was also observed by the Alaskan riometer chain.

**Figure 12.** The anti-sunward, ~ 0.20 kev - 20 kev electron spectra measured by Vela 3A and 4A during the plasma "drop out" are compared with the horizontal components of the Leirvogur and Sodankylä magnetograms.

**Figure 13.** Energetic electrons measured by Vela 4A on August 25-26, 1967. Note the enhanced count rates following the plasma "drop out".

**Figure 14.** The Kiruna and Reykjavik riometer data are shown with the horizontal components of the Sodankylä and Leirvogur magnetograms. Leirvogur and Reykjavik are both in Iceland and Sodankylä and Kiruna are in Sweden. All of the stations were near the midnight meridian during the August 25-26 auroral substorm.
Figure 15. The ionospheric absorption and variation in the horizontal component of the geomagnetic field observed at the Syowa, Antarctica station are plotted with the similar data obtained in Iceland. Leirvogur, Iceland, and Syowa, Antarctica are magnetically conjugate locations.

Figure 16. Geomagnetic tail configuration (Dessler, 1968) similar to Axford et al., but having a neutral line located about 20 RE behind the earth.

Figure 17. Schematic representation of a symmetrical merging region and the plasma flow in the vicinity of the neutral line.

Figure 18. The energetic electrons (E > 40 kev) measured by Vela 4A have been transposed 35 minutes later in time and plotted with the same time scale as the horizontal component of the Leirvogur magnetogram.

Figure 19. Samples of the electron energy density (187 ev - 18 kev) taken with the analyzer looking toward the sun, and away from the sun at the time of the plasma "drop out" measured by Vela 3A.

Figure 20. Electron number density and current observed at Vela 3A simultaneous with variations in the horizontal component of the Leirvogur magnetogram.

Figure 21. Location of the various ground stations plotted on a magnetic local time (MLT), invariant latitude (\Lambda) polar plot. The magnetic local times of the stations shown in this figure were calculated for 2300 universal time. Due to the off-centered non-aligned magnetic dipole axis, the magnetic local time is a function of both geographic latitude and longitude. The
difference in local time and magnetic local time is often quite small and this figure also approximates the local time of each station.

Figure 22. Ionospheric absorption measured simultaneously at the magnetical conjugate stations, Reykjavik and Syowa. The Reykjavik records were off-scale throughout most of this event, but the prominent absorption peaks coincide quite well with the peaks at Syowa.

Figure 23. Variations in the horizontal component of the geomagnetic field observed simultaneously at the magnetically conjugate stations, Leirvogur and Syowa. These data and those in Figure 22 suggest that the original disturbance started in the vicinity of the equatorial plane.

Figure 24. The ionospheric absorption measured at Kiruna is shown with the horizontal component of the Sodankyla magnetogram. The weak bay at ~0007 UT and the broad ionospheric absorption event at ~0030 UT suggests that a disturbance began to the north and then moves slowly equatorward.

Figure 25. Horizontal and vertical components of the Leirvogur and Sodankyla magnetograms recorded during the August 25-26, 1967 auroral substorm. These data indicate that a disturbance moved northward over both stations at ~2315 UT, and at ~0000 UT started to progress southward.

Figure 26. Features of the ionospheric absorption pattern measured by an Alaskan riometer chain near local-noon. The sharp spikes in the data and the event at ~0100 UT are effects of solar x-rays and should not be associated with the auroral disturbance. These solar x-rays were also detected by Vela 3A and 3B (see Figure 11).
Figure 27. The equatorward motion of the disturbance region at local-noon. The time indicated on each contour characterizes the extent of the disturbed region at that time.

Figure 28. The count rate of the \(>50\) kev x-ray channel is compared with the horizontal component of the College magnetogram for the August 25-26, 1967 balloon flight. The symbol "P" indicates the presence of x-ray pulsations with half-widths of 5 to 10 seconds.

Figure 29. The x-ray fluxes \(>25\) kev, \(>50\) kev, and \(>100\) kev measured by Rice University's balloon flight 7 during the August 25-26, 1967 auroral substorm. The data are averaged over one minute and the faster pulsations which occurred between 0000 UT and 0010 UT are not evident.

Figure 30. The ionospheric absorption measured by the Ft. Yukon riometer is compared with the high altitude balloon x-ray data. The balloon was launched from Ft. Yukon and was situated almost directly overhead the entire duration of its flight.

Figure 31. The fine structured x-ray variations observed at the onset of the intense electron precipitation over the high altitude balloon. A power spectra analysis of these data revealed a 24 second periodicity.

Figure 32. The ratio of the \(>100\) kev x-ray fluxes to the \(>25\) kev x-ray fluxes corrected for background, observed during the period of intense electron precipitation.

Figure 33. The features of the ionospheric absorption detected near the dusk meridian. The position of the Antarctic stations, South Pole and Byrd, are indicated by the negative invariant latitudes.
Figure 34. The ionospheric absorption measured by the Great Whale River riometer array. There are five riometers in this array which view the polar sky to the north, south, east, west, and overhead.

Figure 35. The ionospheric absorption measured by the Byrd riometer array. The eastward looking riometer in the Byrd array had malfunctioned prior to the absorption event. Byrd and Great Whale River are conjugate stations and have similar riometer arrays.

Figure 36. The eastward progression of the peak absorption activity projected out a MLT, Λ, polar plot. All wavefronts are drawn at 10 minute intervals.

Figure 37. The westward progressions of the absorption activity projected on a MLT, Λ, polar plot. All wavefronts are drawn at 10 minute intervals.

Figure 38. A composite plot of the auroral zone disturbance pattern projected onto a MLT, Λ, polar plot. All wavefronts are drawn at 10 minute intervals. The time contours are best estimates of the disturbance motion and where no data are available the contours have been broken.

Figure 39. The disturbance pattern shown in Figure 38 projected onto the magnetic equatorial plane. The disturbance which started at L = 6 is seen to propagate around the world in a manner similar to that predicted by Kavanagh et al., (1968).

Figure 40. The daily-disturbance variation observed by several low latitude magnetic observatories. The first indication of activity occurred at 2315 UT at all observatories.

Figure 41. The flux of electrons, $E_e > 0.4$ Mev and $E_e > 1.1$ Mev, observed by ATS-1 during the polar substorm. The dashed lines are the
statistical quite day flux levels. The 3 hour planetary index, \( k_p \), is plotted for the same time interval. The greatly reduced count rates are indicative of an expanded magnetosphere. Since the radial gradient in energetic particle distributions falls off more rapidly for the higher energy particle variations, the \( E_e \gtrsim 1.1 \) Mev electron profile can be used to ascertain adiabatic magnetospheric motions.

**Figure 42.** The \( \gtrsim 0.4, \gtrsim 0.6, \gtrsim 0.8, \gtrsim 1.1, \gtrsim 1.3 \gtrsim 1.5, \) and \( \gtrsim 1.9 \) Mev electron fluxes observed by ATS-1 near local noon. The second non adiabatic electron increased seen in the three lowest energy channels, are the return of the first sharp "spikes" of electrons after drifting around the world. The increases and decreases in electron count rate seen simultaneously in all energy channels, being most pronounced for the higher energies, are due to adiabatic expansion and compression of the magnetosphere.

**Figure 43.** The ATS-1 magnetometer data observed near local noon during the auroral substorm. The horizontal component is 10 – 20 below its normal level also indicating an expanded magnetosphere. The variations in the horizontal component between \( \sim 2330 \) and \( \sim 0130 \) suggests that the magnetosphere was undergoing large scale adiabatic fluctuations during the polar substorm.

**Figure 44.** A parametric determination of the time and location of the acceleration, of the energetic electron detailed by ATS-1 near local noon. (See the text for a discussion of this technique.) The slope of this curve is, \( t_0 \), the time of the acceleration and the \( y \)-intercept, \( d \), is the distance to the origin of the acceleration, in degrees.
Figure 45. The origin of the energetic electrons necessary to explain the onset time dispersion observed at ATS-1.

Figure 46. A parametric determination of the time and location of the acceleration region, of the energetic electrons detected by ATS-1 near local-noon using only those data which indicated enhanced count rates. (See the text for a discussion of this analysis.) The magnetospheric electric fields used in this analysis varied from 0 kv to 180 kv.

Figure 47. The energetic electron fluxes measured by ATS-1 near magnetic midnight on April 2, 1967. This event and the one depicted in Figure 48 are to be compared with the similar August 25-26 event shown in Figure 42.

Figure 48. The energetic electron fluxes measured by ATS-1 near the dawn-meridian on March 18, 1967.

Figure 49. The time dispersion in the arrival of the electron spikes and the half-widths of these spikes are plotted versus local time. The delay in the arrival of the electrons and their "smeared out" appearance imply that they originated near midnight. The data used in this analysis were presented in Figures 42, 47, and 48.

Figure 50. The time between subsequent peaks in each energy channel for the March 18, April 2, and August 25, 1967 events are plotted together with the calculated Hones-Roederer electron drift periods, as a function of energy.
FIGURE 1
FIGURE 4
FIGURE 5
Figure 7
**Figure 12**

- Counts per sample
- Universal time: August 25-26, 1967
- SODANKYL
  - $100 \gamma$
- LEIRVOGUR
  - $500 \gamma$

**4A Electrons** (174 ev - 18.5 keV)

**3A Electrons** (187 - 18 keV)
Figure 13

VELA 4A ENERGETIC ELECTRONS

- ST CHANNEL 9 (electrons 450 keV - 2.25 MeV)
- PKGMA 2 (electrons > 40 keV)

Universal Time August 25-26, 1967
FIGURE 14

RELATIVE ABSORPTION

KIRUNA

SODANKYLAA

100 \gamma \ H

REYKJAVIK

500 \gamma \ H

LEIRVOGUR

UNIVERSAL TIME AUGUST 25-26, 1967
Figure 15
FIGURE 22

IONOSPHERIC ABSORPTION RELATIVE UNITS

REYKJAVIK, ICELAND

SYOWA ANTARCTICA

UNIVERSAL TIME AUGUST 25-26, 1967
FIGURE 30
FIGURE 32

The diagram illustrates the ratio of counts for energy levels greater than 100 keV and greater than 25 keV, with the time period from August 25-26, 1967. The x-axis represents the ratio, while the y-axis shows the count ratio from 0.0000 to 0.0200.
TAILFIELD OF 15 $\gamma$
BEYOND 12 $R_E$

FIGURE 39
SAN JUAN P.R. AUG. 25-26, 1967

FREDERICKSBURG, VA.

TUCSON, ARIZONA

HONOLULU, HAWAII

FIGURE 40
Figure 44

\[ V_d(E) t(E) = V_d(E) t_0 + d \]

- \( t_0 = 16.4 \) min
- \( t_0 = 21.8 \) min
- \( t_0 = 29.2 \) min

\[ V_d(E) [\text{degree - sec}^{-1}] \]
\[ V_d(E) t(E) [\text{degrees}] \]
\[ V_d(E) t(E) = V_d(E) to + d \]

**FIGURE 46**
DAY 92 (APRIL 2) 1967

FIGURE 47
FIGURE 48
TIME DISPERSION BETWEEN 0.4 Mev AND 0.8 Mev electron "SPIKES"

0.4 Mev electron "SPIKE" WIDTH AT HALF - MAXIMUM

FIGURE 49