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INJECTION OF VAN ALLEN RADIATION
DURING POLAR MAGNETIC SUBSTORMS

By

Doris Helena Jelly, B.A.

ABSTRACT

Precipitation of energetic electrons at auroral zone latitude shows two maxima, one just prior to midnight for soft (low energy) electrons associated with polar magnetic substorms and one for harder particles in the mid-morning hours. It is found that increases in precipitation in these two regions frequently show a one-to-one correspondence. The maximum flux of semi-trapped electrons of energies ≥ 40 kev measured by the Alouette I satellite in the morning hours is larger by a factor of about 5 (on the average) shortly after a night-time negative bay on the magnetometer compared with shortly before. The morning cosmic noise (riometer) absorption also increases by an average of about 1 db after the onset of a night-time polar substorm. These observations are consistent with the concepts of bulk motion (convection) of the magnetosphere, of the existence of a maximum flux limit for stably-trapped energetic electrons, and of injection of energetic electrons into the outer radiation belt during substorms.

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DORIS HELENA JELLY, B.A.

A thesis submitted to the Faculty of
Graduate Studies in partial fulfilment
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ABSTRACT

The relation between the aurora and the Van Allen radiation has been an enigma since the discovery of the Van Allen radiation during the I.G.Y. Early models described the radiation zone first as a source from which the auroral particles leaked and then later as a sink which was refilled at the time of aurora. Recent observations have indicated that both models may apply but at different times of day. Near local midnight, active visual aurora forms occurring at the time of polar magnetic substorms have been thought to be associated with "splashes" of low energy electrons (~ 10 kev). The Van Allen region may be replenished with particles by such electron splashes. During local morning hours, uniform mantle aurora detected spectroscopically has been considered to be produced by more energetic electrons (~ 40 kev) leaking from the Van Allen region; i.e., the region acts as a source. These higher energy precipitated electrons, referred to below as "drizzle", are thought to produce ionization which causes a type of radio-wave absorption in addition to the mantle aurora.

The present study was designed to determine if there were a connection between individual nighttime splash and morning drizzle events. If an increase in either trapped or precipitated electrons followed splashes, it might be considered as evidence that electrons had been injected at the time of the splash. Nighttime splashes were selected from ground-based data.

Simultaneous morning particle effects were sought both in fluxes of trapped electrons (> 40 kev) detected by Alouette I and ground based observations of auroral absorption of radio-waves detected by 30 Mc/s riometers.

Increases in both the fluxes of trapped electrons and the intensity of auroral absorption were found to occur during local morning hours at about the same Universal Time as nighttime splashes. The flux of trapped electrons increased by about a factor of 5. Auroral absorption increased on the average by 1 decibel and the maximum absorption occurred about an hour after the splash event. Although the earliest onset of splash events is difficult to determine, the average time delay between splash and drizzle events is found to be 10 minutes, a time too short to be interpreted as the drift time of newly injected electrons. However, the maximum of the absorption effect occurring about an hour after the splash is consistent with the drift to morning hours of new electrons injected at the time of the splash. The time of onset of drizzle events is discussed in terms of an electric field being switched on just prior to the splash events. The effectiveness of splash events in producing drizzle events, found to depend on the level of geomagnetic disturbance and probably on the size of the event, is suggested as evidence in support of predicted limits on the number of stably trapped particles in the radiation zone.

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Injection of Van Allen Radiation

During Polar Magnetic Substorms

CHAPTER I

Introduction

The Van Allen radiation belts are thought by many to be the most outstanding discovery of the IGY. The radiation, particularly in the outer belt, was immediately considered to be associated with the visual aurora. In two early models put forward to relate the phenomena, the radiation belts were described first as a "leaky bucket" (1) and then as a "splash catcher" (2). The "leaky bucket" model pictured the aurora as being produced by trapped electrons leaking from the radiation zone but it was soon found that the supply of trapped electrons was inadequate to produce intense aurora. In the "splash catcher" model, the radiation belts were thought to be replenished at the time of auroral occurrences, a view that is not entirely satisfactory either, since the aurora is thought to be produced by lower energy particles than had been detected in the trapped radiation.

Both these models were also in difficulties because the phenomena occurred at different local times. The most active visual aurora was known to occur most frequently just before local midnight, whereas the maximum fluxes in the Van Allen belt were found during local morning hours. Since then the problem has been partly resolved by two new observational results. Fluxes

of low energy electrons detected by Injun III maximized at night and hence could account for the visual aurora. Nonvisual aurora detected spectroscopically was found to have a maximum during local morning hours such that it could be associated with the maximum of the Van Allen particles. The nighttime phenomena hereafter referred to mainly as splashes might be thought of as effects associated with low energy electrons as in the "splash-catcher" model. The morning events could be considered as a steady "drizzle" from the trapped regions as pictured by the "leaky bucket" model. The purpose of the present work was to determine if there were any connection between the two types of events. In particular, if increases in the trapped particles or drizzle effects followed splash events, they could be interpreted as evidence that splash events injected particles into the trapping regions. Such an observation would be of considerable significance in the formulation of a theory to account satisfactorily for the auroral and trapped radiation phenomena.

In order to state the problem more explicitly in terms of current knowledge, a general description is given first of the solar wind, the magnetosphere, the radiation belts and auroral observations. The statement of the problem is followed by a description of the method and observations. Then a brief outline of pertinent auroral theory is included in terms of which the observations are discussed and the conclusions stated. Two appendices are added with details of particle orbit theory and the experimental techniques.

I-1 Solar Wind and the Magnetosphere

A solar corpuscular radiation was suggested by early investigators. Following their ideas, the first calculations of velocity and density of a corpuscular "solar wind" are attributed to Biermann ⁽³⁾, who showed that a fairly intense flux of low energy solar protons was necessary to explain the features of a certain class of comet tails. Then in 1954, Chapman ⁽⁴⁾ suggested that the solar corona extended all the way out to the earth and that magnetic storms on the earth are caused by outbursts of solar plasma. The existence of the solar wind has now been confirmed by satellite measurements of particle fluxes and velocities. The bulk velocity has been found to be in the range of 300 - 800 km/sec and the plasma density ranges between 0.5 and 10 cm^{-3} , (Snyder and Neugebauer ⁽⁵⁾) and is considered to be mainly protons and electrons. The average thermal energy of the protons (a few ev), is small compared with the energy of the bulk motion (about 1 kev).

In leaving the sun, charged particles of sufficient density will drag magnetic field lines with them according to the frozen field concept. The field lines will remain tied to the sun and so will take up an Archimedes spiral shape as the sun rotates. As the wind blows past the earth, it distorts the earth's magnetic field in the manner shown in Fig. 1. On the sunward side the field lines are compressed until the pressure from the terrestrial field equals the pressure from the solar wind. Field lines from the polar regions are carried with the plasma past the earth into a

Figure 1 The magnetosphere showing the distortion produced in the geomagnetic field by the solar wind. The dotted area indicates the region of stably trapped Van Allen radiation.

"tail" very roughly analogous to the comet tails mentioned above. The volume carved out of the solar wind in this manner by the earth's field was termed the magnetosphere by Gold ⁽⁶⁾ and its shape and extent downwind in the lee of the earth are current topics of conjecture.

An important feature of the magnetic field is the "neutral sheet" in the tail on either side of which the magnetic field is approximately anti-parallel (Ness ⁽⁷⁾). The field is maintained in this configuration by the plasma pressure in the neutral sheet. An increase in magnetic pressure is thought to lead to field annihilation which is of importance to auroral theories and is discussed below.

As well as detecting the solar wind, satellites have also measured the interplanetary magnetic field which is predominantly the magnetic field frozen into the solar wind. It is found to be of the order of 5γ with variations up to 10 or 20 γ ⁽⁸⁾. Rather significantly, both the solar wind velocity and disturbances in the interplanetary magnetic field have been shown to be correlated with the planetary magnetic index K_p which gives a three-hour average of the disturbance of the earth's field. This is highly suggestive that disturbances on the earth may find their source in disturbances in the solar wind. Whether the most important factor is the solar wind or the interplanetary magnetic field or the rate of change of either is not yet known.

I-2 The Van Allen Radiation

O'Brien states the definition, "Van Allen radiation is composed of naturally occurring energetic particles trapped by the geomagnetic field" (9). In describing the radiation belts, he treats only particles with energies greater than about one kev. They exist within the magnetosphere in regions where the effects of collisions and the gravitational field are negligible. The particles can be "trapped" in the geomagnetic field if the field is ordered and where the magnetic field energy density is greater than the charged particles' kinetic energy density. It should be noted that most measurements of the Van Allen radiation have been made with counters having a threshold of about 40 kev for electrons and so the distribution of lower energy electrons is still not well known.

The motion of the particles is comprised of three main components; viz. cyclotron oscillation about the field lines, latitudinal motion along the field lines and a longitudinal drift on a magnetic shell about the earth. The dynamics of the particle motion pertinent to the present work are outlined in Appendix I.

Observations of Distributions in the Van Allen Zones

The Inner Zone

The inner zone is defined to extend from the lower boundary of trapped particles at $L \sim 1.1$ to $L \sim 2.0$ where L , a coordinate defined by McIlwain (see Appendix I) is approximately the equatorial radius of a magnetic shell measured in earth radii. Protons of

energies up to several hundred Mev are thought to carry the bulk of the energy in the inner zone. The zone is relatively stable with the main loss mechanism probably due to atmospheric loss. The source of the inner zone protons is debated. Hess and others ⁽¹⁰⁾ ⁽¹¹⁾ have suggested neutron albedo decay products of galactic cosmic rays as the most likely source. Pizzella, McIlwain and Van Allen ⁽¹²⁾ observed abrupt temporal variations associated with solar proton events and major geomagnetic storms. From this, they concluded that this indicated a source more impulsive in nature than the neutron albedo decay theory would predict. Whatever its source, the time constant of the inner zone usually appears to be of the order of several weeks to a year.

The Outer Zone

The outer zone is defined to exist from $L \sim 2$ out to the boundary of trapping, $L \sim 10$. In comparison with the inner zone the fluxes vary greatly with time and geomagnetic activity. The outer boundary is strongly controlled by local time, varying on the average from a λ of 75° at noon to 70° at midnight (McDiarmid and Burrows ⁽¹³⁾) where λ , the invariant latitude, is based on McIlwain's L parameter (see Appendix I). The latitude of the trapping boundary is of concern to the present work which considers some phenomena which occur at the boundary and others which are known to be well within the trapped region.

Although protons carry a large proportion of the energy right out to the trapping boundary, electron fluxes dominate in observations of the outer zone because of their greater velocities. The time-averaged flux of electrons at 1000 km for $L \sim 2$ to $L \sim 10$ was $j(E_e \geq 40 \text{ kev}) \sim 10^5 \text{ particles cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1}$. The spectrum becomes "softer" with increasing L where "softer" is used to indicate a relative increase of low energy particles. Few measurements have been made of electrons of energies less than 40 kev. Results from Injun III ⁽¹⁴⁾ indicate that at $\sim 10 \text{ kev}$ there are large fluxes ($> 10^7 \text{ cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1}$) at high latitudes at night. These fluxes are at latitudes such that they are considered to be injected from outside the stably trapped regions. They are evidence of the splashes referred to in the present study.

I-3 Auroral Phenomena

Although much has been written on the visual aurora, little of the detail will be included here. Of rather more interest in the present work are the more general features and the gross associations with other phenomena. Auroral morphology has been studied statistically by Davis ⁽¹⁵⁾ and on an individual basis by Akasofu ⁽¹⁶⁾. The latter's approach appears to be the more satisfactory. Sandford ⁽¹⁷⁾ has examined the intensity of aurora in the Antarctic region in what has turned out to be a very illuminating study. Associations between aurora and various geomagnetic data have been examined by many workers, Morozumi ⁽¹⁸⁾, Ansari ⁽¹⁹⁾ and Heppner ⁽²⁰⁾, to name a few. Morozumi showed that the phenomena that he was observing had a diurnal pattern with two maxima, one in the evening and one in the morning. Hartz and Brice ⁽²¹⁾ clarified and extended this idea by compiling a summary of many aurorally associated phenomena, and compared them with particle measurements from satellites. From the resulting pattern they suggested separate origins for the two maxima. The present work relates particularly to one of the questions posed in their paper. The rest of this section is devoted to a summary of works of Akasofu, Sandford and Hartz and Brice, with special attention to features having a bearing on the present work.

Auroral Morphology - Akasofu

To study simultaneous changes of aurora over a large section

of the polar region, Akasofu used all-sky camera data recorded during the IGY at North American and Eastern Siberian stations. The all-sky camera, as the name implies, photographs the sky to the horizon. From one station, a circle of radius about 500 km can be seen at auroral heights (about 100 km). Using the network of stations, Akasofu was able to conclude that the aurora was a very large-scale phenomenon extending along the entire auroral zone in the dark hemisphere.

The most violent auroral phenomena were referred to by Akasofu first as "break-ups" and later as "auroral substorms". In this work they are considered to be a manifestation of "polar magnetic substorms" a term used to include various associated phenomena. The substorms are now thought to be produced by splashes of electrons. Although the terms have somewhat different connotations, "splash" and "substorm" are used interchangeably in the present study.

An auroral substorm is a disruption of the stable arcs lying along parallel geomagnetic latitudes which are characteristic of quiet times. Substorms occur most frequently just prior to local midnight but affect the auroral forms far to the east and west, i.e. towards morning and evening hours. They are divided into two phases, the expansive phase and the recovery phase. The expansive phase starts with a sudden brightening of a quiet arc along a few thousand kilometers of its length. Then the arc "breaks up" into a large bulge around midnight which moves rapidly northward, eastward and westward. The northward and westward motions are of the order of

1 km/sec. If the substorm is weak, the outward motion is very limited and the disturbance is called a "pseudo breakup". The break-up phase which Akasofu describes as explosive lasts less than 10 minutes. During the expansive phase which continues for the next twenty minutes, i.e. while the bulge reaches its northernmost motion (up to 80°), folds are formed in the evening sky, and propagate westward. Arcs near the dawn meridian disperse into cloud-like patches. Patches of illumination also appear south of the bulge.

The recovery phase is defined to start when the northernmost band begins to return south. This it does at a much reduced speed. Motion continues to the west but also at a slower speed. In the morning hours, to the south of the auroral zone, diffuse patches drift eastward at a speed of the order of 300 m/sec. All the activity ceases in 2-3 hours and quiet arcs dominate the sky again. The whole sequence may repeat several times throughout the night and during very disturbed times, substorms may overlap, a second breakup occurring before the first storm has subsided.

Akasofu also commented on the disturbances in the earth's magnetic field at the time of auroral substorms. He observed that the breakup is accompanied by a sharp negative change in the horizontal component (called a negative bay) with amplitude ranging from 100 to 2500 γ . Magnetic disturbances of a less well defined nature accompany the diffuse patches in the morning hours.

Mantle Aurora - Sandford

Sandford, using the intensities of the 6300, 5577, and 3914 $\text{\AA}$

emissions from Antarctic stations during the IGY, derived very interesting patterns. He divided the aurora into two types, discrete emissions, and diffuse emissions. The discrete emissions refer to all forms of aurora that have structures on a relatively small scale and would include all of the forms in the patterns described by Akasofu. The diffuse emissions are widespread glows with little or no small scale structure which, although sometimes detectable either by eye or all-sky camera, are usually not noticed because of the lack of contrast. Mantle aurora, in particular, he defined as a non-visual type of aurora.

Sandford found distinct differences between the patterns of the discrete emission (the Akasofu morphology) and the mantle aurora. The discrete emissions lie on an eccentric circle passing through 70° at midnight and 80° at noon.* The maximum of the mantle aurora lies on a line of constant latitude at about 70° . Latitudes referred to are "auroral" latitudes used by Sandford and defined as the distance of the station from the auroral pole (120°E , 77°S). There were two maxima in 5577 and 3914 Å emissions from the mantle aurora, one in the evening hours and the other which is more pronounced in the morning hours. By contrast the most active auroral forms have one maximum at night. From Sandford's work, it is obvious that mantle aurora must be considered in auroral theories. His main conclusion was that the mantle aurora contributed a major portion of the night sky emissions. It is suggested by Hartz and Brice

* (It should be noted that because the radius of the austral auroral zone is about 5° less than that of the boreal zone, these latitudes would correspond to about 65° and 75° for the northern zone.)

(see next section) that the mantle aurora is associated with phenomena produced lower down in the ionosphere by more energetic particles than those that cause the discrete forms.

Hartz and Brice

These authors examined various aurorally associated phenomena to establish the gross features of precipitation of the auroral particles. They considered statistical data only, most of it already published in the literature. They were concerned mainly with latitude, time and height variations of the various data. They used both geomagnetic latitude which is based on a dipole approximate and invariant latitude without distinguishing between the two. They also used geomagnetic time which, for the purposes of this study, does not differ significantly from local time.

To indicate the variety of phenomena associated with visual and sub-visual aurora, the following list of the data that they considered is included here:

1. Aurora - Sandford's spectroscopic data
2. Auroral absorption - radio wave absorption as measured by riometers (see Appendix II)
3. Radio aurora - radar echoes associated with aurora
4. Magnetic variations - magnetic bays and micropulsations
5. VLF emissions known as "hiss" and "chorus"
6. Ionospheric density - F layer and E layer variations
7. X-rays - from balloon observations
8. All-sky camera data
9. Direct particle measurements from satellites.

From the average time-latitude distributions of these phenomena, they constructed a precipitation pattern, their Fig. 19 which is reproduced here as Fig. 2. As shown in the diagram they concluded that the data could best be represented by two zones, overlapping at about 65° at midnight, but differing by about 10° at noon, where the latitudes refer to the northern hemisphere.

They divided the observations into two broad categories of discrete and diffuse events. The discrete events include aurora having distinct forms, abrupt auroral absorption, bursts of VLF emissions or auroral hiss, negative magnetic bays with abrupt onsets, and short duration bursts of soft electrons. The diffuse events are associated with mantle aurora, slowly varying auroral absorption, relatively constant VLF emissions (chorus) continuous fluxes of electrons of energies greater than 40 kev. The discrete events they consider to be intense and localized, with irregular fluctuations. They are thus pictorially described as a "splash" suggestive of the splash-catcher model referred to above. The diffuse events are more continuous and cover a larger area. They are termed a "drizzle" as from a leaky bucket. Because of the observed particle distributions and the heights of the events the splashes are thought to be caused by softer particles and the drizzle, producing effects at lower heights, is due to harder particles.

The inner curve of Fig. 2 represents the softer "component". It maximizes about 2200 hours, just prior to local magnetic midnight, where most of the splash events occur. The outer curve maps out

Figure 2 Precipitation patterns (Hartz and Brice). The density of the symbols denotes the average density in latitude and time of two types of precipitation. The triangles represent the softer splash precipitation and the dots represent the harder drizzle precipitation.

the harder component, the drizzle, which has a maximum in the morning about 0800 hours. The locus of the soft lower energy precipitation is suggested to be the boundary separating closed dipole-like magnetic field lines and the open lines extending into the magnetospheric tail as shown in Fig. 1. If this is the case, it is suggested, the splash events occurring most frequently around midnight must correspond to injection of particles from the tail region, probably from the region of the neutral sheet. Similarly it is argued that the drizzle component maximizing in the morning hours must come from deep within the closed field lines and thus must originate from at least semi-stably trapped particles in the Van Allen radiation belts. They raise the question of whether individual morning drizzle events should be intimately connected with nighttime splashes.

CHAPTER II

The Problem

Aurora has long been thought to be a nighttime phenomenon having a maximum at midnight or slightly before. The particles in the Van Allen belts that were first detected and thought to be associated with the aurora were electrons of energies greater than 40 kev. In an early model, O'Brien ⁽¹⁾ proposed that the aurora was produced by Van Allen radiation leaking from the trapped region which acted as a source (the leaky bucket). It was soon shown that this model was inadequate because the trapped radiation was insufficient to account for the most intense auroras and the maximum of the Van Allen radiation occurred in the morning whereas the active forms of aurora has a maximum at night. O'Brien's second suggestion ⁽²⁾ that the trapped radiation zone acted as a sink rather than a source stemmed from observations of increases of trapped 40 kev electrons at the time of auroras (splash catcher); however, the aurora is known to be produced by electrons of energies much less than 40 kev. And so the connection between Van Allen particles and aurora remained a dilemma with aurora produced at night presumably by soft electrons which had not been detected directly and the Van Allen radiation composed of more energetic electrons having a maximum for both trapped and precipitated components in the morning hours.

Two kinds of observational evidence which have since become available have helped to clarify the picture, namely Sanford's

measurements of mantle aurora and measurements of lower energy electrons ($E \sim 10$ kev). Sandford found that the mantle aurora had a maximum intensity in the morning hours at latitudes corresponding to the maximum Van Allen radiation. Hartz and Brice have suggested that the radiation zones may be acting as a leaky bucket in producing the mantle aurora at that time. The second important observations were the splashes of low-energy electrons detected at night by Injun III. These and lower energy electrons probably could account for discrete auroral forms and suggested the possibility of injection of particles into semi-trapped orbits in the manner of the splash catcher model.

The purpose of the present work was to determine if there is a connection between the splash and drizzle events. An increase in either trapped electrons or drizzle effects following splash events would be interpreted as evidence of injection of particles at the time of the splashes. In testing the hypothesis, satellite data were used to study the trapped particles and ground based observations of auroral absorption were used to detect the drizzle effects.

CHAPTER III

Method

Two methods of testing the hypothesis are suggested:

- (1) to examine the fluxes of trapped electrons following nighttime splashes using satellite data for the electrons and ground-based data for splashes;
- (2) to look for evidence of increased precipitation (drizzle) during morning hours following nighttime splashes using ground-based data only.

Because of the known association between various kinds of data, there is potentially a wide choice of data for selection of events. The Alouette particle data which were made available are most complete in the area of Alaska. In order that the satellite would be passing through the Van Allen region during the maximum radiation, morning passes should be selected. The requirement for observations of splashes during local night at the same UT time as the local morning satellite passes meant that splashes had to be selected from data recorded at stations in Siberia. Therefore, magnetograms available until the end of 1962 from Tixie Bay and Dixon Island in Siberia were chosen to select the nighttime events for comparison with the satellite particle data. (See Figure 3). Riometer data which were considered most appropriate for selecting both types of events from ground-based data were available from stations in Canada and Sweden, separated by about seven hours in longitude, a separation suitable for simultaneous observation of nighttime and morning events.

Figure 3 Map showing stations referred to in the text. Contours show the intersection of magnetic L shells with the 100 km level above the earth's surface. The L shell number (1.5 to 100) is approximately the distance from the earth's centre to the point where the shell crosses the equatorial plane (see Appendix I).

Brief comments on the experimental techniques are given here; the details are given in Appendix II. The Alouette satellite at 1000 km was said to be detecting trapped electrons of energies greater than 40 kev when pitch angles of the particles were between 70° and 90° . The riometer detects ionization at 80 - 100 km, corresponding to heights at which precipitated electrons from 10 - 100 kev are stopped by the atmosphere. The magnetometer detects currents in the height range of 100 - 140 km presumably produced by particle influxes. The magnetometer is sensitive to precipitation effects over a much wider area than is the riometer and hence does not provide as precise measurements. For this reason riometer data were chosen where they were available.

III-1 Satellite Electron Data and Magnetograms

The satellite passes that were selected satisfied the following criteria:

- (a) trapped electrons of energies ≥ 40 kev were being detected;
- (b) local times at the satellite were between 0300 and 1200 hours;
- (c) there were two passes separated by at most 3 hours; i.e. either consecutive passes or two passes with one missing in between.

For the purposes of this work, the pairs of passes selected in this way are referred to as "consecutive" passes.

The pairs of passes were then divided into the following three categories according to the magnetograms at Tixie Bay and Dixon Island;

- (a) those with magnetic disturbances within four hours prior to the first pass of the pair;
- (b) those with the onset of a negative bay (substorm) in the horizontal component between the first and second pass corresponding to local times between 1800 and 0300 hours at Tixie or Dixon;
- (c) those without any magnetic bay between the passes.

The first category, (a) was considered to be contaminated by substorms already in progress. The second category (b) formed the experimental data being sought and the third group (c) was used for a control. There were 11 pairs of passes in the substorm group (b), and 10 pairs in the control group (c).

III-2 Riometer Data

30 Mc/s riometer records from two Canadian stations, Cape Jones and Churchill were used to select the splash events and similar records from Kiruna, Sweden, were used to select drizzle effects. (The locations of the stations are shown on the map in Fig. 3). In order to seek a definite result only those events which were large with well-defined onsets were selected. The following criteria aided in choosing the splash events:

- (a) an undisturbed record for the previous hour;
- (b) an abrupt onset with a rate of increase of absorption of at least 1 db per 5 minutes;
- (c) duration greater than 1 hour;

- (d) maximum amplitude exceeded 1 db for more than five minutes
i.e. excluding small events with one large spike;
- (e) onset between 1800 and 0300 hours local time.

For each of the events selected according to the above description, the absorption values at 15 minute intervals were read from the Kiruna records for an hour before to two hours following the events. Onset times of drizzle events at Kiruna were recorded if they could be determined to within 5 minutes. The absorption at Kiruna and the onset times of both splash and drizzle events for the years 1962 - 63 - 64 formed the basic data for the study.

The absorption at Kiruna was averaged in a "superposed epoch" manner, in which the onset time of the splash event defined the zero time. The differences in onset times were determined between Cape Jones and Churchill and between those two stations and Kiruna when onsets could be established there. The effects of different levels of magnetic disturbances were also studied using the planetary magnetic index K_p for reference. Details are given in the next section.

CHAPTER IV

Observations

IV-1 Satellite Electron Data and Magnetograms

As was mentioned above, there were 11 pairs of Alouette passes between which a splash event was recorded at Tixie Bay, or Dixon Island and 10 pairs where no event was observed at Tixie or Dixon to be used as a control. These are listed in Table I (a), (b) and an example, 8 Oct. 1962 is shown in Fig. 4. The horizontal magnetic components, H, from Dixon Island and Tixie Bay are at the top. Both show a very large magnetic bay at ~ 1740 UT, corresponding to just before midnight at Dixon Is. and just after midnight at Tixie. (A very small magnetic bay with a much slower onset occurred at College starting about the same time). Next is shown a tracing of the riometer record at Fort Yukon somewhat to the north of College, ($\lambda \sim 67^\circ$). A rather shallow absorption bay occurred about the same time as the magnetic bays over Siberia. Local time at Fort Yukon was about 0800. At the bottom of the diagram are listed relative maximum fluxes of > 40 kev electrons detected by Alouette I during six consecutive passes over North America in the same time interval. During the first three passes, the flux was at a fairly constant level. Between the third and fourth passes, the maximum flux increased by more than an order of magnitude. It was between these transits that the splash event occurred over Siberia. The satellite was located at

TABLE I

(a) Passes with Bays

PAIR NUMBER	DAY 1962	FIRST PASS NUMBER UT		SECOND PASS NUMBER UT		FIRST FLUX $\times 10^5$	SECOND FLUX $\times 10^5$	LT
1	3 Oct.	59	1325	61	1650	6.5	6.5	10.8
2	4 Oct.	74	1545	76	1920	5.1	14.3	10.8
3	7 Oct.	115	1600	117	1925	4.9	6.7	10.2
4	8 Oct.	129	1630	130	1815	5.1	70.0	10.0
5	9 Oct.	140	1150	141	1335	5.0	30.4	10.2
6	29 Oct.	415	1535	417	1905	3.3	6.8	7.6
7	2 Nov.	467	1110	469	1430	4.4	10.2	6.8
8	4 Nov.	496	1400	497	1545	10.3	95.8	6.6
9	6 Nov.	523	1330	524	1515	6.8	56.2	6.3
10	7 Nov.	534	0850	536	1220	8.5	18.2	6.2
11	8 Nov.	550	1255	551	1445	5.0	39.2	6.0
Average						5.9	32.2	

List of pairs of consecutive Alouette I passes between which magnetic bays occurred over Siberia. Each pair is identified by a number and the date (first and second columns). The individual passes are identified by number and universal time (third to sixth columns). The maximum flux (averaged over a 10 second interval) of trapped electron $E > 40$ kev observed over North America is given in units $\text{cm}^{-2} \text{sec}^{-1} \text{ster}^{-1}$ (seventh and eighth columns). Local time of the satellite is given in the last column.

TABLE I(b) Passes without Bays

PAIR NUMBER	DAY 1962	FIRST PASS		SECOND PASS		FIRST	SECOND	LT
		NUMBER	UT	NUMBER	UT	FLUX	FLUX	
						$\times 10^5$	$\times 10^5$	
1	7 Oct.	114	1407	115	1600	2.4	4.9	10.5
2	8 Nov.	127	1300	128	1445	5.1	5.1	10.3
3	1 Nov.	455	1350	457	1725	6.2	3.7	7.0
4	5 Nov.	507	0920	508	1100	8.7	6.7	6.6
5	5 Nov.	510	1435	511	1620	8.5	8.6	6.5
6	5 Nov.	512	1808	513	1955	6.8	3.5	7.0
7	7 Nov.	539	1740	540	1925	5.0	5.2	6.6
8	9 Nov.	562	1000	563	1145	4.9	5.0	5.9
9	25 Dec.	1195	1940	1196	2125	4.4	6.5	10.1
10	28 Dec.	1233	1435	1234	1620	4.3	5.0	10.0
Average						5.6	5.4	

Fluxes of trapped electrons (≥ 40 kev) during consecutive passes with no bays between passes. Columns are the same as in (a).

Figure 4 A typical example showing the correlation between a midnight splash event and morning increases of both auroral radio-wave absorption and the trapped electron flux. The splash event appears as a large bay in the horizontal component of the earth's magnetic field (measured in γ 's) starting at (a) Dixon Island at 0220 LT and (b) Tixie Bay at 2235 LT. Auroral absorption (at 27.6 Mc/s.) at Fort Yukon (c) near College, Alaska, is measured in decibels increasing downwards. In (d) are shown relative maximum fluxes of trapped electrons ($E > 40$ kev) detected by the Alouette I satellite during six consecutive passes over North America.

$\lambda \sim 64.0^\circ$ and local time of 1019 hours at the time of the maximum. The flux during the last two passes of the sequence was less than during the fourth pass but had not returned to the prestorm level. The first and second passes formed one of the pairs of consecutive passes in the group without bays and the third and fourth passes comprised one of the pairs in the group with bays. In Table I it is seen that of the 11 cases with bays, 10 showed an increase during the second pass and the 11th remained at the same level; of the 10 cases without a bay, 6 showed increases, 1 showed no change and 3 decreased in level. In one unusual sequence of three passes which were not included in the passes selected, the flux during the second pass was an order of magnitude greater than during the first and third. Positive bays occurring at Tixie between the first and second pass were accompanied by negative bays at College. This is interpreted as evidence of injection in the vicinity of College accounting for the increased flux during the second pass.

To demonstrate the average differences in electron flux with and without splash events, means were calculated and are shown in Table II. For the passes bracketing magnetic bays, the electron flux increased more than 5 times from the first to the second pass compared with a slight decrease (.96) when no event occurred. Sequences such as that shown in Fig. 4 tend to add weight to the significance of the result. The limited observations presented here suggest that a significant increase of trapped electrons follow splash events.

TABLE II

	CONSECUTIVE SATELLITE PASSES	FIRST FLUX	SECOND FLUX	RATIO	NO. OF PAIRS OF PASSES
		$\times 10^5$	$\times 10^5$		
(a)	with bays	5.9	32.2	5.4	11
(b)	without bays	5.6	5.4	.96	10

Averages of the maximum fluxes of trapped electrons shown in Tables I(a) and (b) are given for consecutive passes (a) with bays between them and (b) without bays. The ratios of the average maximum fluxes in the second passes of the pairs to the first passes are given in the fourth column.

IV-2 Riometer Data

A representative example of the events chosen is shown in Fig. 5, in which the Churchill riometer record is shown at the top. Cape Jones in the middle and Kiruna at the bottom for the period 0000 to 0700 UT 5 April, 1964. The two events which occurred at Churchill and Cape Jones are typical of the splash events i.e. abrupt onsets (breakup) and usually irregular recovery. The events between 01 and 02 were chosen although definitely borderline because the event at Churchill lasted barely half an hour and at Cape Jones, because the first increase was barely at a rate of 1 db/5 min. The times of splashes, S, were defined for Churchill and Cape Jones as 0140 and 0125 UT for the first event and for the second at 0328 and 0313 UT.

The two events at Cape Jones and the two at Churchill have been referred to as if they were separate events. Indeed their times of onsets are separated by 15 minutes at the two stations, but it is felt that they do represent only two distinct events each with a northward and/or westward motion according to the picture of Akosofu's substorms. The similar shapes of the events at the two stations is evidence of this. Churchill is some hundreds of kilometers west of Cape Jones, but more significantly it is farther north, ($\lambda \sim 70^\circ$ for Churchill compared with $\lambda \sim 67^\circ$ for Cape Jones). It is thought that these events start at Cape Jones latitude or farther south and move northward towards Churchill where their first appearance is 15 minutes later, in agreement with Akosofu's northward

Figure 5 Typical examples of radio wave absorption effects of midnight splash events and a coincident morning event as they appear on 30 Mc/s riometer records. Absorption increases downward on a logarithmic decibel scale from an undisturbed level which is shown as a thin line. The curvilinear time scale is indicated at hourly intervals. Splashes, marked S, appear at Churchill and Cape Jones. A well-defined coincident morning event at Kiruna is marked D_1 , D_2 .

moving bulge. This point is explored in detail below.

Turning to the Kiruna riometer, there is no definite event between 0100 and 0200 hours. Then a slow decrease in noise level starts at 0305 changing to a faster rate at 0324. These times have been designated D_1 and D_2 , i.e. slow drizzle and fast drizzle. The event at Kiruna continues for some $2\frac{1}{2}$ hours, a much longer duration than the event at Churchill and somewhat longer than at Cape Jones. Nevertheless, it is felt that there is a definite connection between the event at Kiruna and that at the Canadian stations. The onsets are of particular interest. Considering the times that were originally selected, the timing sequence is D_1 , S_{CJ} , D_2 , S_{CH} . Looking at the record, the Cape Jones substorm could have started at 0305 with splash at 0313. The D_1 phase could have started as late as 0308, i.e. after the Cape Jones start. This point is also continued below. The main features to note in this diagram in addition to the starting times is the difference in appearances of the events, splashes -- abrupt, irregular, shorter; drizzle - slow onset, smoother, longer lasting, features that are characteristic of events at the specific local times and latitudes. ←

To show that the distribution of splash events selected in a rather arbitrary manner was representative of the midnight events described in the literature, the times of onsets of the events for Cape Jones and Churchill were plotted in a histogram, shown in Fig. 6. The Churchill events have a maximum between 0400 - 0500 UT and Cape Jones events between 0300 - 0400 UT. These times ←

Figure 6 Universal time dependence of onsets of splash events at Cape Jones and Churchill. Local midnight is 0500 and 0600 UT respectively.

correspond to 22 - 23 local time at the stations, in good agreement with the average time of occurrence of splash events shown by Harts and Brice. The local time at Kiruna corresponding to the most likely time of onset of substorms at Cape Jones and Churchill would be 04 - 06 LT so that it is well located in time to observe morning drizzle effects associated with the splash events at the Canadian stations.

The absorption scaled from the Kiruna records at times of splash events at Cape Jones and Churchill was recorded at 15 minute intervals. The results are shown in Fig. 7 where the average absorption at Kiruna at each 15 minute interval is plotted for events selected at Churchill and those selected quite independently at Cape Jones for each of the years 1962, -63, -64, separately and the total combined. The number of events making up each average is shown beside the station name. Zero time is the time of occurrence of the splash. The main feature to note in this figure is the increase in absorption at Kiruna of about 1 db above the background level following the splash events. On the average there is little if any increase in absorption 15 minutes before the splash event occurs; however, again on the average, there is a slight increase in the absorption at Kiruna by the time of the splash over Canada. The absorption steadily increases to a maximum of more than a decibel above normal 45 minutes after events at Churchill and about an hour after events at Cape Jones. This difference in time of maximum is probably because of the apparent motion of splash events referred above i.e. they occur earlier at Cape Jones than at

Figure 7 Average absorption at Kiruna associated with splash events at Churchill and Cape Jones. Absorption in decibels was averaged at 15 minute intervals for all events selected at each station during each year. Zero time is the time of the splash. Numbers of events are given with each curve.

Churchill. This tends to give a later starting time at Churchill and hence a shorter delay time to the onset of an event at Kiruna, exactly the opposite to what would be expected considering only electron drift times.

To demonstrate that the absorption at Kiruna was associated with the splash events, the absorption at the same times on random days was averaged in the same way. The days prior to the occurrence of events were considered to be random, i.e. for the splash that occurred at Cape Jones at 0809 UT on 14 February, 1963, as a control the absorption at Kiruna was scaled with 0809 UT on 13 February, 1963 as zero time. The comparison was made only for Churchill 1963 events. The result is shown in Fig.8. There is little increase in absorption throughout the random curve which may be indicative of the average diurnal variation at Kiruna. The reason for the lower level before events is uncertain. It may indicate that, in general, quiet conditions prevail before a substorm occurs. The increase in absorption at Kiruna following events at Churchill does seem to be significantly greater than on the random days.

Brief mention was made above of the difference in onset times of splash events between Cape Jones and Churchill. To study this in greater detail, the time differences between all events that occurred at both these stations were separated into 10 minute intervals. The results are shown in Fig. 9. Negative times are defined to mean that the event was seen first at Churchill, positive means first at Cape Jones. It is seen that of the 98 events

Figure 8 Comparison between the average absorption at Kiruna

- (a) associated with splash events at Churchill, 1963 (see Fig. 6)
- (b) at random times where random times are taken to be on the previous day but the same zero time in UT as each of the splash events included in curve (a).

seen at both stations 76 (or 75%) appeared earlier at Cape Jones. The median time difference is of the order of 10 minutes. This is consistent with the explanation for the time shift in the average absorption curves shown in Fig. 7. Apparent motion of splash events of the nature suggested by the data are presumably due to motions of the source. Such motions make it difficult to determine the earliest onsets of events without a large network of stations to study.

Of greater import to the present study than the time differences between onset times of splash events, are the differences in onset times between splash and drizzle effects which might be expected to give drift times from injection to precipitation. Because of the ambiguity discovered in the onset times of splashes, the time difference is known only approximately. This was determined from the present data and is shown in Fig. 10. Here the events are divided, again in 10 minute time intervals, into those that appeared at Kiruna first (on the left), and those that started earliest at either of the Canadian stations (on the right). Many more of the splash events start before the drizzle starts over Kiruna. (Starting time at Kiruna means the D_1 phase if there was one). The median time difference is about 10 minutes.

To determine if there were any consistent sequence between D_1 , D_2 and S onsets, those drizzle events were selected which clearly exhibited the two onset rates, slow and then fast. The results are shown in Table III. There were 22 events of this type sufficiently clearly defined such that onset times could be determined

Figure 9 Distribution of time differences between onsets of splash events at Churchill and Cape Jones. The time differences are divided into 10 minute intervals with positive differences indicating that an event occurred first at Cape Jones.

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Figure 10 Distribution of time differences between onsets of splash events (the earlier of Cape Jones or Churchill onsets when an event occurred at both station) and morning drizzle events at Kiruna. Time differences are divided into 10 minute intervals with positive differences indicating that the splash occurred first.

TABLE III

EARLIEST ONSET	Ch or CJ (S)	D ₁	D ₁ and D ₂
NUMBER OF CASES	14	6	2

Numbers of cases with earliest time of
 (a) Churchill or Cape Jones splash events,
 (b) D₁ at Kiruna or (c) D₁ and D₂ at
 Kiruna where D₁ and D₂ refer to slow and
 fast drizzle.

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to the nearest 5 minutes. For 14 of the 22 events, the onset at Kiruna was clearly either later than or at the same time as the earlier of the onsets at the two Canadian stations. In 6 cases D_1 preceded onsets at both Canadian stations and in 2 cases both the D_1 and D_2 phases occurred before the splash started. The median duration of the D_1 phase was about 15 minutes.

The number of events such as the second of those shown in Fig. 5, which demonstrated a clear connection between splash and drizzle effects was sufficient to produce the well defined average curves shown in Fig. 6. However, there were events such as the first one in Fig. 5 which did not show any specific correlation. There were also very definite splash events during which there was no absorption whatsoever recorded by the Kiruna riometer. To find out how many splash events were followed by drizzle effects and to determine the relative efficacy of selecting splash events at Cape Jones and Churchill, the splash events were divided into the following three categories:

- (a) those that occurred at Churchill only;
- (b) at Cape Jones only;
- (c) and at both stations.

The categories were then divided, according to the absorption conditions at Kiruna, into three groups of events as follows:

- (i) no absorption at Kiruna during the whole three hour period scaled;
- (ii) no increase in absorption at Kiruna comparing $\frac{3}{4}$ hour after zero time with $\frac{1}{4}$ hour before;

(iii) an increase in absorption at Kiruna comparing $\frac{3}{4}$ hour after to $\frac{1}{2}$ hour before the splash.

The results are shown in Table IV as numbers of cases and as percentages. The group (iii) showing numbers of events with an increase in absorption at Kiruna following splash events is, of course, the result being sought in this study and is seen to include a considerably higher number of events than groups (i) and (ii). In using one station only to select splash events with associated drizzle, Churchill appears to be more effective than Cape Jones, i.e. 74% compared with 62%. However, by using the two stations, the efficiency is appreciably improved in that 89% of all splash events observed at both Churchill and Cape Jones were followed by an increase in absorption at Kiruna. If we consider that the no-absorption cases constitute a real effect (see later) and no-increase cases represent the error rate, it would appear that with 80% of splashes selected at the two stations increases at Kiruna are genuinely associated.

Group (i) where there was no effect at Kiruna is of particular interest. The fact that the percentage occurrence of this type drops significantly when two stations are used to select the splash events suggests that the events must be at least of a minimum size before there is a drizzle effect associated. They may be the "pseudo breakups" of Akosofu. Another possible factor influencing the association might be the general level of magnetic disturbance at the time of the event. To investigate this possibility, the planetary magnetic indices, K_p , for the 12 hours before the splash

TABLE IV

ABSORPTION AT KIRUNA	(a) SPLASH AT CHURCHILL ONLY	(b) SPLASH AT CAPE JONES ONLY	(c) SPLASH AT CHURCHILL AND CAPE JONES	TOTAL
	152	120	98	370
(i) No Absorption	17 (11%)	21 (17%)	2 (2%)	40
(ii) No Increase	23 (15%)	25 (21%)	9 (9%)	57
(iii) Increase	112 (74%)	74 (62%)	87 (89%)	273

Summary of absorption conditions at Kiruna associated with nighttime splash events identified at:

- (a) Churchill only;
- (b) Cape Jones only and
- (c) at both station.

The events are divided according to the absorption at Kiruna into the following groups:

- (i) no absorption during the three hour period scaled;
- (ii) no increase in absorption comparing 3/4 hours after zero time with 1/2 hour before zero time;
- (iii) an increase comparing 3/4 hour after zero time with 1/2 hour before.

event occurred were compared for events with Kiruna absorption and those without. Table V shows the result which appears to be fairly conclusive with the average K_p almost twice as great when drizzle effects are associated with splash events compared with occasions when there is no drizzle. It would appear to be a necessary condition that there should be a magnetic disturbance already in progress before there is much drizzle associated with splash events.

To determine the relative importance of magnetic disturbance, the percentage occurrence of splashes at Churchill during the hours 00 - 09 UT for each K_p level was determined as shown in Table VI where it is seen that the probability of splashes occurring during magnetically quiet times is very low and increases with K_p to $K_p = 5$. The decrease at $K_p \geq 6$ may be because of the statistically low number or may very well be because well-defined, isolated splashes do not occur when the disturbance level becomes too high. Absorption tends to become continuous during very disturbed periods.

TABLE V

HOURS BEFORE EVENT	12 to 9	9 to 6	6 to 3	3 to 0	0
ABSORPTION AT KIRUNA	3.1	3.3	3.4	3.6	4.0
NO ABSORPTION AT KIRUNA	1.6	1.8	2.0	1.8	1.9

Average planetary magnetic index K_p for four 3-hour periods prior to splash events at Cape Jones and for the three hour period in which the event occurred (last column). The events are separated according to whether or not there was absorption at Kiruna during the three hour period scaled.

TABLE VI

K_p	0	1	2	3	4	5	≥ 6
Total K_p 's	489	834	751	646	377	135	52
Events at Churchill	1	10	36	76	92	50	14
%	0	1	5	12	24	37	27

Percentage occurrence of splash events as a function of K_p . The total number of 3-hour periods are given during which the K_p was at each level for hours 00 - 09 UT (18 - 03 LT at Churchill) for the years 1962 - 63 - 64. The number of events occurring at each K_p level are shown along with the percentage that these K_p form of the total number of K_p 's at each level.

CHAPTER V

Theory

An impression of the present status of theories concerning aurora and the radiation belts is given by these recent comments: "The Earth's Radiation Belts", a review article published by White ⁽²²⁾ in 1966 is prefaced by the following statement: "In eight years since their discovery, the belts have trapped many researchers", and in 1965, Chamberlain ⁽²³⁾ wrote in "The Present Status of Auroral Theory", "Auroral theory has a long and unsavoury history ... and we have not progressed very far." Individual auroral or geomagnetic theories deal with many facets of the total phenomenon. Here only a few theories having a bearing on the relation between auroral phenomena and the radiation belts are of direct concern although many other aspects will be necessarily interconnected. The features of importance to the present work are mechanisms for injection of material at high latitudes on the night side of the earth, the means whereby some particles are trapped either temporarily or permanently in the radiation belts, energization of particles, and methods of altering pitch angles such that the electrons precipitate during local morning hours. So far, there is no generally accepted theory for any of these features. Models which permit possible explanations are given here for injection, acceleration and precipitation.

In a very good survey, Levy, Petschek and Siscoe ⁽²⁴⁾ have

considered various aspects of magnetospheric flow, with particular emphasis on the flow of the solar wind over the magnetosphere. They consider in some detail a model proposed by Dungey ⁽²⁵⁾, in which magnetic field lines in the solar wind having a southward component, connect with field lines on the sunward side of the earth. The solar wind in moving past the earth then carries the field lines with it across the polar regions into the tail of the magnetosphere where reconnection of field lines takes place. This process is shown schematically in Fig. 11 in which the numbers give the sequential positions of field lines. Because of the insulation of the lower atmosphere, the field lines and hence the ionization associated with them are free to move over the atmosphere at heights in the ionosphere. Above about 150 km, both electrons and ions move with the field lines. Below about 80 km, the collision frequency with neutrals is so high that both electrons and ions move with the neutrals. In the region 80 - 150 km, the electron gyrofrequency is greater than the collision frequency so that electrons are constrained to move with the field lines whereas the ion collision frequency is greater than the ion gyrofrequency so the ions move with the neutrals. Thus in this height range, currents flow predominantly due to the Hall conductivity.

As a magnetic field line is pulled from the sun side of the magnetosphere across the polar cap into the tail, another field line (1') must move outward to take its place. This sets up a convection system of the magnetic field lines and also of the

Figure 11 Schematic representation (Brice) of the convection pattern established by a southward directed interplanetary magnetic field line connecting with the earth's magnetic field on the sunward side. The numbers indicate successive positions of a field line. Arrows ($\rightarrow$) indicate the direction of motion of field lines and plasma flow.

plasma within the magnetosphere. Currents associated with the motion of the feet of the field lines map out current systems in the ionosphere which, as Levy et al have shown, are in agreement with the current systems deduced from magnetometer observations. Motions of aurora may also be partly due to the convection pattern.

One feature of this model that is of particular interest to the present work is the possible reconnection of field lines. Increased pressure in the magnetospheric tail may be sufficient to overcome the particle pressure in the neutral sheet that keeps the field lines apart. After reconnection, a field line would move in towards the earth carrying along plasma. Since both ends of the field lines are connected to the ionosphere, some of the particles could be injected into the ionosphere in a manner which would have the features of the break-up or splash events i.e. abrupt onset, irregular, occurring around local midnight at conjugate points in the northern and southern auroral zones. Various mechanisms have been suggested for accelerating particles in the tail region to the energies of auroral particles, however none has yet received widespread support. Because such acceleration is not of direct concern to the present work, possible mechanisms are not discussed here. The fact that electrons are injected with auroral energies from the tail seems to be reasonably well accepted.

A convection model has been developed in considerable detail by Axford and Hines ⁽²⁶⁾. They assumed that the geomagnetic field is enclosed in a limited volume and that the magnetosphere rotates

with the earth. There would then be two components to the convection pattern, one due to the rotation of the earth and the other imposed by the solar wind. Although they assume a viscous-like interaction rather than merging of field lines to be the driving mechanism, the existence and some features of the convection pattern are independent of the form of interaction assumed. They found that such a convection pattern would map into areas on the earth corresponding approximately to the auroral zones.

The convection motion of the field lines will have an associated electric field given by $\vec{E} + \vec{v}_B \times \vec{B} = 0$, where $\vec{v}_B$ is the velocity of the magnetic field lines and hence of the magnetospheric plasma. The electric field associated with the motion of the field lines is shown schematically in Fig. 12. In the polar regions, the magnetic field lines moving from noon to midnight give rise to an electric field directed approximately from morning to evening. Similarly, in the equatorial plane the convection of the field from midnight to noon gives an electric field that is also parallel to the morning-evening line. Such an electric field would accelerate trapped electrons in their normal drift from PM to AM on the night side and would decelerate then on the day side.

Even if the mechanism for accelerating auroral particles to the energies of Van Allen particles were known, the means whereby they become trapped and untrapped in the Van Allen zones must be explored. Little is known of means of trapping particles, but in a method suggested by Dungey⁽²⁷⁾ for untrapping, whistlers interact with energetic electrons changing their pitch

Figure 12 Schematic representation (Brice) as seen from the sun of the electric field, E , associated with the motion of the field lines shown in Fig. 11. In the plane of the diagram the field lines in the polar regions are thought to move away from the sun; in the equatorial region, they are moving towards the sun. Arrows give the direction of the electric field.

angles by diffusion or a random walk towards the loss cone. Brice (28) showed that such a change in particle pitch angles was associated with an increase in wave energy so that the process could become unstable. Kennel and Petschek (29), in a detailed analysis of the mechanism, showed that for stably-trapped electrons the instability condition implied a maximum allowable flux of stably trapped particles. Any increase above the threshold would initiate the instability which would then precipitate electrons until the flux was reduced to the threshold level. The fluxes of electrons with $E > 40$ kev are observed to be close to the limit for stable trapping beyond $L = 4$, indicating that some acceleration and/or injection mechanism exists which keeps the flux of particles close to their precipitation limit.

CHAPTER VI

Discussion

From the observations presented above it is apparent that there is an association between increases of trapped electrons at 1000 km during morning hours and nighttime magnetic bays seen on magnetograms. This association was confirmed by the correlation shown to exist between increases in auroral absorption during morning hours and the occurrence of nighttime splash events. The discussion of the results will refer mainly to the absorption data with which it was possible to establish onset times.

As Hartz and Brice and others have suggested, from the latitude and time of occurrence, the abrupt splash events such as those at Cape Jones and Churchill appear to occur at the boundary between "closed" magnetic field lines and those that extend into the tail of the magnetosphere. The morning maximum of precipitation referred to as drizzle and typified here by absorption at Kiruna, would seem to come at latitudes well within closed field lines. The fact suggested previously by Ortner and Riedler ⁽³⁰⁾ and definitely established here, that the two types of events are intimately connected has interesting implications. It suggests that with each splash event some particles are injected into semitrapped orbits in the outer Van Allen radiation zone near the midnight meridian. The electrons drift from west to east, but some are soon precipitated.

This picture is too simple for several reasons. First, the morning precipitation is known to be much harder than the splash events. The two kinds of precipitation are, therefore, either from different populations or the injected electrons are accelerated before they precipitate. A second difficulty with the simple picture is the time separation between onsets of splash events at Cape Jones or Churchill and drizzle events at Kiruna. The time difference, found to be about 10 minutes, is much less than the normal drift time between the stations for 40 kev electrons, which is known to be at least an hour from Equation (20) Appendix I. Another unexplained feature of the precipitation is its time of maximum shown by Hartz and Brice to be about 0900 hours. With simple drift and precipitation it would seem that the precipitation should be continuous after injection. The effect of magnetic disturbance is also unexplained.

The mechanisms outlined in Section IV have been used by Brice (private communication) to account for some features of the observations. In particular, an electric field $\vec{E} = -\vec{v}_B \times \vec{B}$ due to the motion of the magnetic field lines will affect particles being injected and particles already stably trapped. If it were directed from AM to PM as was suggested, it would have the greatest effect in accelerating electrons in their normal drift motion from west to east on the night side. Evidence has been produced by Carpenter and Stone (31) of an electric field being 'switched on' about 30 minutes before a substorm. From an inward motion of magnetospheric plasma observed in whistler studies, they deduced that, at an equatorial

distance of about 4 earth radii, there was an electric field corresponding to a potential difference of up to 3 kilovolts per earth radius. The field would probably be present from the time of first merging of magnetic field lines on the sunward side of the earth. Trapped electrons on the night side would be accelerated very soon afterwards and perhaps before any injection would take place if it is due to subsequent merging of field lines in the magnetospheric tail.

Precipitation would start only when the flux density of electrons had reached the threshold found by Kennel and Petschek, assuming their model for precipitation to be correct. The electrons precipitated could be either electrons that had been already trapped or the newly-injected electrons. If the process is such as Brice has suggested, the time difference between injection of particles at night and precipitation in the morning is dependent on (a) the start time and magnitude of the electric field compared with the time of splash, (b) fluxes and energies of particles injected and (c) fluxes and energies of particles already trapped. The precipitation could in fact start before injection takes place, a situation which is suggested by some of the observations. It is tempting to suggest that the precipitation during the D_1 phase, when both D_1 and D_2 occur, is due to previously trapped particles while the D_2 phase would correspond to the arrival of the highest energies of the newly-injected particles. The average time delay from splash to D_2 of 25 to 35 minutes would be consistent with the drift period of

electrons of roughly 100 kev.

The time difference between the onsets of the events was found to be difficult to determine because of the problem in establishing the earliest onset time of splash events and the lack of definition in the drizzle events. However, the average time of maximum of the absorption at Kiruna is seen to be quite definite (1 hour after Cape Jones splashes and $\frac{3}{4}$ hour after Churchill splashes). The apparent motion of the splash events to higher latitudes which could account for the 15 minute difference is in agreement with the Akasofu model of auroral substorms. Such motions may be accounted for in the Dungey model as successive merging of field lines further away from the neutral sheet corresponding to latitudes closer to the poles. Although no evidence is produced here to prove the association, it is thought probable that the intense, high latitude electron "spikes" reported by McDiarmid and Burrows (32) (33) are associated with absorption splash events. They had suggested that injection at the time of the electron "spikes" could account quantitatively for the source of the outer radiation belt.

The model suggested would appear to explain the occasions when no absorption occurred at Kiruna following some splash events. These events were shown to occur during times of low K_p and probably to be of limited size. It would seem likely then that at such times electrons are injected but because either the injection is small or, during quiet times, the level of trapped particles is particularly low, the threshold level for precipitation

is not reached. This would explain why events seen at both Cape Jones and Churchill are more often followed by absorption at Kiruna than if the splash is detected at only one of the pair of stations, and why splashes during disturbed times are more likely to produce morning precipitation than splashes during quiet times.

The morning maximum of precipitation is consistent with acceleration of the electrons by an electric field. Without such acceleration, it would seem that the maximum of precipitation should occur at midnight where the injection occurs. From statistical data of auroral absorption, there are known to be two distinct peaks of activity corresponding to the nighttime and morning events⁽²¹⁾. This suggests that during individual events, particles do not precipitate continuously from the splash event around to the east. Data were not available from stations suitably placed to establish the longitude pattern of the events selected for the present study. This point merits further study.

CHAPTER VII

Conclusions

That the level of Van Allen radiation during local morning hours increases shortly after polar magnetic substorms occurring near midnight seems to be well established by the present work. This conclusion results from a study of both satellite and ground-based data. Using Alouette I observations of fluxes of electrons of energies ≥ 40 kev, intensities of trapped electrons were found to increase by more than a factor of 5 following substorms (referred to also as splashes). The drizzle of electrons precipitating from the Van Allen regions during local morning hours produce auroral absorption which was found to increase on the average by more than 1 decibel following nighttime splash events. The splash events have previously been associated with the injection of soft electrons from the magnetospheric tail; the morning events are thought to be caused by the precipitation of harder electrons. There is now seen to be a close association between individual events of the two types.

From the absorption data, the onsets of morning events followed the splashes by about 10 minutes on the average, a time delay too short to be interpreted in terms of the normal drift of the electrons from night time to morning longitudes. The initial precipitation has been suggested to be due to previously trapped electrons accelerated by an electric field switched on at the start of a convection process which probably also causes the night time splashes.

The maximum of the morning precipitation following the injection by about 1 hour is consistent with drift times of newly injected electrons of energies of about 40 kev. Therefore the conclusion is drawn that electrons are injected into semi-trapped orbits at the time of splashes.

The morning precipitation does not take place if the general level of magnetic disturbance is low or if the splash event is small. This is suggested as evidence that there is a limit on the number of stably trapped particles which is not exceeded under quiet conditions nor by small events.

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APPENDIX I

The Motion of Charged Particles in the Earth's Magnetic Field

Charged particles moving in the undisturbed earth's field, i.e. the Van Allen radiation, follow very complicated trajectories. However, since particle interactions can be ignored, methods have been developed which are used to describe the motions relatively simply. The development of Heikkila and Axford⁺ will be followed closely in outlining some of the approaches that are used.

The equation of motion of a single charged particle moving in electric and magnetic fields is

$$m \frac{d\vec{v}}{dt} = q \vec{E} + q \vec{v} \times \vec{B} \quad (1)$$

where mks units are used and the treatment is non-relativistic.

If there is no electric field and if the magnetic field is constant in space and time, the kinetic energy, T , of the particle does not change during the motion since

$$\frac{dT}{dt} = m\vec{v} \cdot \frac{d\vec{v}}{dt} = 0 \quad (2)$$

Thus, if the velocity vector is written in the form

⁺ Physics of the Earth's Upper Atmosphere, Prentice-Hall, 1965.

$\vec{V} = (v_x, v_y, v_{||})$ where v_x and v_y are the components perpendicular to the magnetic field and $v_{||}$ is the component parallel to the field, then

$$\frac{2T}{m} = v_x^2 + v_y^2 + v_{||}^2 = \text{constant} \quad (3)$$

Similarly by taking the scalar product of (1) with $\vec{B}$, $v_{||}$ is found to be constant.

The equation of motion reduces to

$$\frac{dv_x}{dt} = \frac{v_y q B}{m}, \quad \frac{dv_y}{dt} = \frac{-v_x q B}{m} \quad (4)$$

where $v_x^2 + v_y^2 = v_{\perp}^2 = \text{constant}$.

The equations (4) have solutions

$$v_x = v_{\perp} \sin(\Omega t + \theta) \quad (5)$$

$$v_y = v_{\perp} \cos(\Omega t + \theta)$$

where θ is an arbitrary constant and Ω is the gyrofrequency given by

$$\Omega = \frac{q B}{m} \quad (6)$$

where the sign of the charge is included. The particle motion is therefore a helical one, composed of a uniform motion parallel to $\vec{B}$

and a circular motion in a plane perpendicular to $\vec{B}$. The pitch angle of the helix is given by the angle $\alpha = \tan^{-1} \frac{V_{\perp}}{V_{\parallel}}$ and the radius of the circular motion is

$$\rho = \left| \frac{v_{\perp}}{\Omega} \right|$$

where ρ is called the radius of gyration or the Larmor radius.

If an electric field is present, particles are then found to have a drift motion perpendicular to the magnetic field. This can be shown by defining a velocity $\vec{v}'$ as follows:

$$\vec{v}' = \vec{v} - \frac{\vec{E} \times \vec{B}}{B^2} \quad (7)$$

Substituting (7) into (1) gives the following equation in $\vec{v}'$

$$m \frac{d\vec{v}'}{dt} = q \vec{E}_{\parallel} + q \vec{v}' \times \vec{B} \quad (8)$$

i.e. in a frame of reference moving with velocity $\frac{\vec{E} \times \vec{B}}{B^2}$, the particle appears to gyrate around the lines of force and to be accelerated along the lines of force because of $E_{\parallel}$. The effect of the $\vec{E}$ field is thus to cause the centre of gyration to drift at a speed $v_D = \left| \frac{\vec{E}_{\perp}}{B} \right|$, perpendicular to $\vec{E}$ and $\vec{B}$, and independently of charge.

The description of the motion of a particle by considering the drift motion of the centre of gyration (the guiding centre) superimposed on the gyration about the field lines can be extended to include motions due to inhomogeneous magnetic fields. This approach, originally developed by Alfven, ⁺ can be used if the radius of gyration is small compared with the size of the inhomogeneities and if the period of gyration is large compared with time variations. Two kinds of magnetic inhomogeneities, both appearing in the earth's field, produce drift motions. The first is a transverse gradient which, in changing the radius of gyration of the particle, produces a drift in the direction

$$\bar{v}_D = \frac{v_{\perp}^2}{2 \Omega B^2} (\bar{B} \times \nabla B) \quad (9)$$

The second is the curvature of the field lines which causes the particles to drift due to the centripetal force, $\frac{m v_{\parallel}^2}{R}$ where R is the radius of curvature. This also produces a drift in the plane perpendicular to the field lines given by

$$v_D = \frac{v_{\parallel}^2}{\Omega R} \quad (10)$$

found by substituting $F_{\perp} = \frac{m v_{\parallel}^2}{q R}$ for E in (7). If local currents

⁺ Alfven, H., and C.-G. Fälthammar, *Cosmical Electrodynamics*, 2nd ed. Clarendon Press, Oxford, 1963.

can be neglected then it can be shown that

$$R^{-1} = \frac{|\bar{\mathbf{B}} \times \bar{\nabla} B|}{B^2} \quad (11)$$

and that $\bar{\mathbf{B}} \times \bar{\nabla} B$ lies in the direction perpendicular to the plane of the field line. (10) can then be written

$$v_D'' = \frac{v_u^2}{\Omega B^2} (\bar{\mathbf{B}} \times \bar{\nabla} B), \quad (12)$$

and the resultant drift in a field with both kinds of inhomogeneity is

$$v_D = v_D' + v_D'' = \frac{v_u^2 + \frac{v_\perp^2}{2}}{\Omega B^2} (\bar{\mathbf{B}} \times \bar{\nabla} B) \quad (13)$$

Since q a q , protons and electrons drift in opposite directions.

In the geomagnetic field, protons drift towards the west and electrons towards the east.

Corresponding to the various motions of particles in magnetic fields, there are three adiabatic invariants governing the motion. These invariants are useful in that they permit generalizations to be made about particles moving in the Van Allen radiation belts. The first invariant, corresponding to the gyration of the particle about the field line, is the magnetic moment, μ , defined as

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$$\mu = \frac{m v_{\perp}^2}{2 B} = \frac{T \sin^2 \alpha}{B} \quad (14)$$

Alfven has shown that μ is a constant even in a non-uniform, time-varying magnetic field provided the variations in the field are small compared with the radius of gyration and the gyrofrequency of the particle. If such is the case,

$$\frac{\sin^2 \alpha}{B} = \text{constant}. \quad (15)$$

This means that particles will tend to mirror in increasing magnetic fields i.e. $v_{\perp}$ increases while $v_{\parallel}$ decreases. At some magnetic field strength, B_m , the motion will all be perpendicular to the field line, i.e. if α_0 and B_0 are the pitch angle and magnetic field strength as the particle crosses the earth's equatorial plane,

$$\frac{\sin^2 \alpha_0}{B_0} = \frac{\sin^2 90^\circ}{B_m} = \frac{1}{B_m} \quad (16)$$

In this way, a particle bounces back and forth between mirror points in each hemisphere. Because of the gradient forces referred to above, it does not stay fixed to one field line but drifts in longitude as well.

The second invariant is derived from the bounce motion, and is defined as

$$I \equiv \int v_{||} ds, \quad (17)$$

where ds is an arc length measured along the guiding centre between mirror points. Because of the invariance of I , the particle drifts across longitude on a single invariant surface or "shell", and returns to the line of force from which it started.

The periods of the three motions described above are given by the following expressions:

- (i) the oscillation about the field line (Larmor frequency)

$$\frac{1}{\tau_1} = \frac{\frac{1}{2} m v_{\perp}^2}{B}, \quad (18)$$

- (ii) the latitudinal bounce

$$\tau_2 = 2 \int_A^{A^*} \frac{ds}{v_{||}} \quad (19)$$

where A and A^* are the mirror points.

- (iii) the longitudinal drift (Lew⁺)

$$\tau_3 = 172.4 \frac{\gamma}{\gamma^2 - 1} \frac{1}{m r_0} \frac{G}{F} \text{ minutes} \quad (20)$$

for the relativistic case where $\gamma = (1 - \beta^2)^{-\frac{1}{2}}$ where $\beta = \frac{v}{c}$ and c is the velocity of light, m is the rest mass in units of electronic rest mass,

+ Lew, J.S. J. Geophys. Res., 66, 2681, 1961.

and G/F is the ratio of drift period of particles mirroring at latitude λ_m to that of particles mirroring at $\lambda_m = 0^\circ$. G/F is the order of unity and a function of λ_m only.

Typically τ_1 is in the order of milliseconds, τ_2 is in the order of seconds and τ_3 is in the order of minutes to hours.

A co-ordinate system suitable for organizing observations made within the magnetosphere, has been developed by McIlwain⁺ using the invariant properties of the geomagnetic field itself. At a point, A, the co-ordinates he suggested are B and L. B is the magnitude of the magnetic field at A. L is a parameter dependent on both B and I, the invariant parameter now defined as

$$I = \int_A^{A^*} \left(I - \frac{B_1}{B} \right)^{\frac{1}{2}} ds$$

where B_1 is the magnitude of the field along the line of force and B is again the magnitude of the magnetic field at A. The defining function $L = f(B, I)$ used by McIlwain is such that L remains almost constant along a given geomagnetic field line and is approximately the distance from the centre of the earth to the point where the field line crosses the equator. The shell parameter, as L is called, then characterizes the whole toroidal family of field lines having the same invariant I.

McIlwain's co-ordinates have been transformed into pseudo-polar co-ordinates (R, λ) by using the relationships that hold in a

⁺ McIlwain, C.E., J. Geophys. Res., 66, 3681, 1961.

dipole field

$$\beta = \mu_0 M R^{-3} (4 - 3 R/L)^{\frac{1}{2}}$$

$$R = L \cos^2 \lambda$$

where μ_0 is the permeability of free space, M is the dipole moment, λ is called the "invariant latitude" and is widely used in organizing geophysical data even though the co-ordinates as McIlwain originally considered them could not be defined at high latitudes.

Appendix II

Experimental Techniques

(a) The Riometer

The riometer (relative ionospheric opacity meter) was first used by Shain⁺ and later by Little and his colleagues in Alaska.⁺⁺ It is a simple receiver in the V.H.F. range, usually about 30 Mc/s, designed to receive the radio noise emitted by the galaxy. The cosmic noise, as it is called, is equivalent to a stable transmitter with a smoothly varying sidereal period. At the receiver on the ground, variations in the signal intensity, other than the sidereal effect, are due to absorption in the ionosphere.

The incoming signal from the cosmic noise is continuously compared with the output from a noise diode. The difference is used to adjust the noise diode output to the incoming signal. The plate current of the diode is recorded. Ionospheric absorption results in a reduction in the signal input and the noise level is recorded in decibels. Thus differences in output noise level are attributed to absorption in the ionosphere which in turn are thought to be caused by the ionization produced by incoming particles. The dynamic range of the instrument is about 15 db with a resolution of about 0.1 db.

The approximate height of the ionization which reduces the cosmic noise signal can be deduced by considering the propagation of

+ Shain, C.A., Aust. J. Sci. Res. A, 4, 258, 1961.

++ Little, C.G., and H. Leinbach, Proc. I.R.E., 47, 315, 1959.

radio waves through an ionized medium in the presence of a magnetic field. In passing through the ionosphere from x_1 to x_2 , a radio wave is attenuated by the following amount

$$\exp \left\{ - \int_{x_1}^{x_2} k \, dz \right\}$$

where k is the absorption coefficient, and dz is an incremental path length in the direction of propagation.

If the QL (the quasi-longitudinal) approximation is used,

$$k = \frac{\omega_o^2 \nu}{2 c n_r \{ [\omega \pm \omega_H \cos \theta]^2 + \nu^2 \}}$$

where ω_o = plasma frequency

ν = collision frequency

c = velocity of light in free space

n_r = real part of the refractive index

ω = wave frequency

ω_H = gyrofrequency

and θ = angle with the magnetic field.

For riometer frequencies, $\omega \gg \omega_H$, and $n_r \sim 1$, i.e. the absorption is non-deviative.

Therefore

$$k \sim \frac{\nu}{\omega^2 + \nu^2}$$

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The absorption is seen to be a maximum when $\omega = \nu$. Thus the height for most efficient absorption varies with the wave frequency. According to present knowledge of collision frequencies, the specific absorption of 30 Mc/s is greatest at about 80 km whereas higher frequencies are affected more at lower heights and lower frequencies higher up. The 30 Mc/s frequency range is very suitable for studying absorption effects of ionization produced by say 30 - 40 kev electrons since they are thought to penetrate into the atmosphere to about 80 km.

The noise level is recorded on Estherline-Angus chart recorders at the rate of 3" per hour. The record is calibrated either in decibels of noise power or in milli-amps of plate current which can be converted to decibels. The time resolution on the charts is of the order of 1 minute although uncertainties of up to 5 minutes may be introduced if the recorder does not advance the paper at the correct speed. To measure absorption, the undisturbed sidereal variation of the cosmic noise must be subtracted from the recorded noise level. This is the weak point of the technique since the riometer must be very stable over long periods of time in order for the background (the quiet day curve) to be determined. Weathering of the antenna, changes in the ground conductivity, aging of components in the receiver are a few of the factors which may contribute to unreliable data. When the equipment is functioning properly, the accuracy with which the absorption may be measured is about 0.1 db for low values, and up to 0.5 db at the 10 db level.

(b) Alouette I Energetic Particle Detector

The Alouette I satellite was launched at 0605 UT on 29 September, 1962, into a nearly circular orbit at an altitude of about 1025 km, with an inclination of 80° , and a period of 105 minutes. Of the six particle detectors on board, details of which are given by McDiarmid et al⁺ only one is sensitive to particles of significance to the study, that is the Anton 223 Geiger counter which detects electrons of energy equal to or greater than 40 kev. It is located at the end of a cylindrical brass collimator inclined at 10° to the spin axis of the satellite and with an angular aperture of 4.5° . To correct for higher energy electrons entering the detector through the shielding, a small background, determined from another detector ($E > 3.9$ Mev), is subtracted from the count. The 223 counter also responds to protons with energies greater than 0.5 Mev. In comparison with another counter detecting protons in the range of 1 - 7 Mev, the intensity from this counter was at least two orders of magnitude greater than the proton intensity; thus it is thought that protons are not likely to contribute much to the measured fluxes.

A flux-gate magnetometer in the satellite measures the component of the earth's magnetic field perpendicular to the satellite spin axis. This permits the orientation of the particle detectors with respect to the field to be determined. Particles with pitch angles from 70° - 90° are described as "trapped" since

+ McDiarmid, I.B., J.R. Burrows, E.E. Budzinski and Margaret D. Wilson, Can. J. Phys., 41, 2064, 1963.

they will mirror between 700 to 1000 km. Particles with pitch angles less than 45° are referred to as "precipitated" since they would normally mirror below 100 km, but because of their penetration into the atmosphere at these heights, they are lost from the trapping regions.

Normally the corrected counts during 10-second intervals are recorded for periods when the satellite is within line of sight of the telemetry stations at St. John's, Ottawa, Prince Albert and Resolute in Canada and College, Alaska. In the present study, tabulations of the maximum 10-second count during each pass were used to select those passes during which the satellite was detecting trapped electrons. Since these maxima occur in or near the auroral zone, data from the telemetry station at College were most useful.

(c) Magnetometers

Magnetometer records were made available through the IGY World Data Center. Several types of magnetometers are in use and although the particular type of equipment used by the stations was not known, the magnetograms are produced in a standardized form on which three components are recorded; viz. H, the horizontal component, Z, the vertical and D, the declination.