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ELECTRON PRECIPITATION IN THE AURORAL ZONE

R. R. BROWN

Department of Physics, University of California, Berkeley, California

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Abstract. The present experimental knowledge of electron precipitation in the auroral zone is summarized, using observations primarily from riometer, balloon, rocket and satellite studies. This includes the association of electron precipitation events with aurora, magnetic disturbances as well as temporal and spatial aspects of the particle bombardment.

Introductory Remarks

Electron precipitation in the auroral zone has come to be associated with a wide range of phenomena. Thus, when large fluxes of electrons move downward into the atmosphere, at small angles with respect to the geomagnetic field, ground-based instruments generally indicate one or more types of geophysical effects taking place such as geomagnetic disturbances, auroral emissions, enhancements of the electron density in the lower ionosphere as well as bremsstrahlung X-rays at balloon altitudes. While these effects of electron precipitation have been the subject of investigation at high magnetic latitudes for a decade or more, it is only in recent years that direct measurements of the particle influx have been possible by placing particle detectors on rockets and satellites. The results of these studies have now provided better estimates of the electron fluxes and energy spectra at auroral latitudes and thus established a firmer basis for theoretical investigations of the secondary effects taking place in the upper reaches of the atmosphere. However, these advances in technique, while contributing greatly to progress in this area of research, have not rendered obsolete the earlier methods of observation. Rather, by virtue of being relatively fixed in position and making observations a large fraction of the time, techniques utilizing the secondary effects resulting from particle influx have brought forward a number of additional features of electron precipitation. Also, results obtained in this manner have raised several questions of fundamental importance to the dynamics of electrons in the magnetosphere. Thus, in the discussion which follows, consideration will be given to both direct and indirect methods of observation in summarizing the present experimental knowledge of electron precipitation in the auroral zone.

Historical Summary

The first observations in which vehicles carried detectors into electron fluxes precipitating on the atmosphere were made by the group under Van Allen at the State University of Iowa. This "soft radiation", as it was termed (VAN ALLEN, 1957), was encountered at auroral latitudes in the course of a latitude survey of primary cosmic

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radiation when Geiger counters, carried aloft by the "rockoon" sounding rocket technique, reached altitudes in excess of 50 km. Thus, the Geiger counters, instead of counting at a relatively low rate characteristic of the more penetrating galactic cosmic rays passing through the detector, responded to electron bremsstrahlung at rates many times above the cosmic ray background while beyond the atmosphere. These experiments, at about the minimum of the next to last solar cycle, demonstrated that the electrons were mainly in the energy range from 10 to 100 keV and extremely variable in intensity, with fluxes from 10^6 to 10^8 electrons/cm^2 sec. At the time, no associations of the presence of soft radiation were made with visual aurora or other geophysical disturbances.

The next advances in the study of electron precipitation were made with balloon-borne detectors, well beyond the range of the incident electrons but within the reach of bremsstrahlung X-rays propagating downward through the atmosphere. Thus, the group at the University of Minnesota under Winckler, flying Geiger counters in the first magnetic storm of the IGY, found intense X-ray fluxes at balloon altitudes under bright, active auroral forms associated with negative magnetic disturbances (WINCKLER and PETERSON, 1957). These observations at Minneapolis (55.4 °N magnetic latitude) resulted from the fact that large magnetic storms during the period of solar maximum produced electron precipitation over a wide range of latitudes.

Shortly after these observations at sub-auroral latitudes, ANDERSON (1958) detected X-ray fluxes at balloon altitude in the auroral zone (Ft. Churchill, Canada, 69 °N magnetic latitude) with Geiger counters and ionization chambers during the magnetic storm of August 29–30, 1957; however, these X-ray fluxes were not definitely correlated with visible aurora. Later, by including Na I(Tl) scintillation counters, having X-ray detection efficiency two orders of magnitude greater than Geiger counters, in balloon payloads as well as provisions for pulse-height analysis, ANDERSON (1960) was able to obtain the first spectral information on the incident radiation.

Additional rocket flights in the IGY, exposing scintillation counters directly to the particles incident at high magnetic altitude, provided further information on electron precipitation and the production of auroral displays. Thus, MCILWAIN (1960) showed that much of auroral luminosity is produced by low energy ($\sim$10 keV) electrons, with protons carrying only a small fraction of the energy to emitting regions and, consequently, producing little ionization in the atmosphere.

Turning to ionospheric effects, the collisional ionization produced by the entry of precipitating electrons into the atmosphere results in enhanced electron densities in the lower ionosphere and thus increases ionospheric absorption of radio waves. By means of the continuous monitoring technique employing riometers (LITTLE and LEINBACH, 1959), the study of absorption of cosmic radio noise at auroral latitudes was initiated during the IGY. From this, it was found (CHAPMAN and LITTLE, 1957) that absorption effects, termed "auroral absorption", of an irregular nature generally take place during periods of magnetic activity (bays and storms) and are associated with the occurrence of visual aurora, particularly the post-breakup phases. In this connection, it is important to note that the data from balloon flights

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carrying X-ray detectors have shown a strong correlation between X-ray events and increased ionospheric absorption, as recorded by riometers.

The magnetic disturbances at auroral latitudes which were found to be associated with aspects of electron precipitation events, i.e. aurora, increased ionospheric absorption and X-rays at balloon altitude, have long been the subject of study (cf. e.g., CHAPMAN and BARTELS, 1939). These generally involve negative excursions in the field strength at the ground although positive changes are found on occasion. While individual disturbances (bays) may range in magnitude up to several hundred gamma ($1\gamma = 10^{-5}$ gauss) and last an hour or so under fairly simple circumstances, during extended storm conditions magnetic variations become quite complex with numerous bays, larger in magnitude and overlapping in time.

These results then, essentially in hand by the end of the IGY, showed that:

a) electron precipitation appears frequently at auroral latitudes, but reaches sub-auroral latitudes at times of intense geophysical disturbance,

b) the electron influx is characterized by energies in the range from 10 to 100 keV or so, with a fairly steep energy spectrum,

c) electron fluxes above 10 keV are quite variable, ranging from 10^6 to 10^8 cm^{-2} sec^{-1} on occasions, and

d) electron bombardment of the atmosphere occurs during magnetic bays and storms, giving rise to visible auroras, enhanced electron densities in the lower ionosphere as well as X-ray fluxes at balloon altitude for periods of an hour or more.

As such, this information served as the basis of further studies aimed at obtaining a fuller understanding of electron precipitation, its morphology and relation to geophysical phenomena. This effort received a tremendous stimulus with the discovery of energetic particles, both electrons and protons, trapped in the geomagnetic field (VAN ALLEN *et al.*, 1958). Hence, the presence of a large reservoir of radiation only a short distance above the atmosphere raised the possibility that it might be the source of electron precipitation and thus responsible for its associated effects. With the discussion of electron dynamics and adiabatic invariants, perturbing mechanisms were searched for which might release trapped particles into the atmosphere during geomagnetic disturbances. In addition, questions related to the source strength, lifetime and leakage rate of the electrons were explored to determine if the statically-trapped particles could account for the energy dissipated in the atmosphere through the various aspects of electron precipitation.

In the sections that follow, these and other questions will be considered, in the light of results from recent experiments, but first, a fuller discussion will be given to electron precipitation in the auroral zone, with emphasis on the additional features of this process which have been brought forward since the conclusion of the IGY.

1. Ionospheric Absorption Studies

In many ways it is appropriate to begin a discussion of electron precipitation by considering the results obtained from ionospheric studies at high magnetic latitudes.

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This approach has yielded significant information on features of electron precipitation, particularly in recent years after the development of the riometer (*r*elative *i*onospheric *o*pacity *meter*) by LITTLE and LEINBACH (1959). This instrument, operating continuously rather than for brief, widely separated time intervals as the ionosonde, provides information on particle precipitation events at a given location by measuring the cosmic radio noise power that penetrates the ionosphere. While the galactic noise shows a daily variation due to the rotation of the earth with respect to the galaxy, superimposed on the quiet-day records are found additional variations due to ionospheric absorption which result from enhancements of the electron density, either from particles or photons interacting in the atmosphere. From these records, a number of distinct phenomena have been identified: sudden ionospheric disturbances (SID), polar cap absorption (PCA), auroral absorption (AA) and sudden commencement absorption (SCA); only the last two involve electron precipitation and thus are of interest in this review.

A. EXPERIMENTAL CONSIDERATIONS

Before examining results obtained by the cosmic noise absorption technique, certain features should be pointed out as they bear on the limitations of the method and interpretations of results obtained in this way.

1) Riometers have generally employed broad-beam, vertically directed antennas and this places restrictions on the spatial resolution possible in examining the structure of absorption regions; by the same token, it does not indicate the extent to which the antenna pattern is covered with ionization. To illustrate the magnitudes involved, the 3-element Yagi antennas for IGY riometers, operating at 27.6 mc/s, had half-power beam widths of approximately 60° in the E plane and 120° in the H plane, intercepting an elliptical area at the 80 km level of 275 km by 90 km. With more elaborate antenna systems, greater resolution is possible; thus, ANSARI (1963), employing a square array of 16 Yagi antennas, was able to reduce the beam width to $\sim 12°$.

2) By recording the cosmic noise power which penetrates the ionosphere, a riometer integrates the absorption taking place at each level and each direction within the antenna pattern. With a knowledge of the power polar diagram of the antenna as well as an indication or reasonable assumption as to the horizontal distribution of ionization, the obliquity factor may be removed, thus giving the ionospheric absorption in a vertical column. This quantity is of value in examining the additional ionization produced during an electron precipitation event, the absorption of cosmic radio noise passing vertically through the absorbing region being given by

$$I = I_0 \, e^{-\int K \, dh}$$

where K, from magneto-ionic theory (RATCLIFFE, 1959), is expressed in terms of the refractive index μ, the electron density N_e, the electron-neutral collision frequency ν, the radio wave frequency ω, and the angular gyro-frequency about the longitudinal

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component of the magnetic field ω_L, according to

$$K = \frac{2\pi e^2}{mc} \frac{1}{\mu} \frac{N_e \nu}{(\omega \pm \omega_L)^2 + \nu^2}$$

and with the positive and negative signs referring to the ordinary and extraordinary modes of propagation, respectively. (This expression corresponds to the quasi-longitudinal approximation, satisfactory for studies at high magnetic latitudes where the magnetic field and antenna patterns are close to the vertical direction.)

From this, it is evident that the ionospheric absorption which accompanies an electron precipitation event depends on the electron density profile $N_e(h)$, in turn related to the incident particle spectrum and its geometry as well as properties of the atmosphere. While measurements at a single frequency readily show ionospheric absorption during magnetic disturbances, multifrequency measurements are necessary to infer further features of electron density profiles.

3) Another important feature of the riometer is the manner in which it responds, time-wise, to changes in incident noise power. Thus, a differential time-constant circuit discriminates against increases in noise power (interference) by means of a long time-constant, typically 30 seconds, but follows decreases in noise power (absorption) with a short time-constant, around 1 second. This aspect of the instrument itself limits the riometer technique to fairly slow changes in absorption.

4) In order to interpret electron density profiles obtained by multi-frequency riometer observations of absorption events, it is necessary to deduce the corresponding ionization profiles produced by the influx of particles from a knowledge of ionospheric processes. The procedures used in doing this are based on methods developed for analyzing PCA events; with the lower energies involved in auroral absorption and sudden commencement absorption events, this amounts to extrapolating the ionospheric model to somewhat higher altitudes.

Following this approach, at each level, the ionization rate, $q(h)$ ion pairs/cm^3 sec, and the electron density $N(h)$, electrons/cm^3 are related by the continuity equations:

$$\frac{dN_e}{dt} = q + KnN^- + \rho SN^- - \eta n N_e - \alpha_D N_e N^+$$

$$\frac{dN^-}{dt} = \eta n N_e - KnN^- - \rho SN^- - \alpha_i N^- N^+$$

$$\frac{dN^+}{dt} = \frac{dN_e}{dt} + \frac{dN^-}{dt}$$

where N^+ and N^- are the ionic densities, N_e the electron density, n the appropriate neutral density at the height h in the upper atmosphere, depending on whether the term in the continuity equations is connected to attachment or detachment. The important processes involved in these expressions are (1) electron-positive ion production by ionizing collisions of incoming particles, q; (2) electron-positive ion recombination, α_D; (3) negative ion-positive ion recombination, α_i; (4) formation of

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negative ions by electron attachment, η; (5) electron production by collisional detachment, K; and (6) photo-detachment of electrons from negative ions, ρS.

In this approach it is assumed that the principal positive ions are N_2^+, O_2^+, and NO^+, with essentially the same recombination coefficients (α_D and α_i) and that the dominant negative ions are those of oxygen, O_2^- and O^-. Electrons attach to O_2 and O by three-body of two-body processes, depending on altitude and concentrations, and electrons are freed from the negative ions due to photodetachment by day and collisions with neutral constituents at night.

For slowly varying events, to be discussed in a later section, the equilibrium solution may be used to obtain the ionization rate:

$$q = (1 + \lambda)(\alpha_D + \lambda\alpha_i) N_e^2$$

where λ is the negative ion-electron ratio

$$\lambda = \frac{\eta n}{\rho S + Kn + \alpha_i N^+}$$

On the other hand, with rapid changes in ionization rate, as sometimes observed by balloon-borne X-ray detectors, the electron density varies with time and requires integration of the continuity equation:

$$\frac{dN_e}{dt} = \frac{q}{1 + \lambda} - (\alpha_D + \lambda\alpha_i) N_e^2$$

For the case where the ionization rate undergoes a discontinuous increase, from $q=0$ to $q=q_0$ at $t=0$, the electron density rises toward the equilibrium value:

$$N = N_0 \tanh(\sqrt{\alpha Q t})$$

where

$$N_0 = \left[\frac{q_0}{(1 + \lambda)\alpha}\right]^{1/2}, \quad Q = \frac{q_0}{1 + \lambda}, \quad \alpha = \alpha_D + \lambda\alpha_i$$

while for the case where a steady ionization rate is abruptly ended, from $q=q_0$ to $q=0$ at $t=0$, the electron density decays toward zero according to

$$N = \frac{N_0}{1 + \alpha N_0 t}$$

where

$$N_0 = \left[\frac{q_0}{(1 + \lambda)\alpha}\right]^{1/2}$$

These considerations indicate that ionospheric levels have "time constants", governed by the rates at which electrons and ions are formed and destroyed. Whether absorption events vary at either extreme, fast or slow, a knowledge of these ionospheric processes is required to relate ionization profiles to electron density profiles, or vice-versa. By way of summary, recent estimates of these rate coefficients are given in

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TABLE I

Estimates of ionospheric rate coefficients

Dissociative Recombination	$\alpha_D \sim 2 \times 10^{-7}$ cm^3 sec^{-1}
Mutual neutralization	$\alpha_i \sim 10^{-7}$ cm^3 sec^{-1}
Attachment (three body)	$\eta_3 \sim 1.5 \times 10^{-30}$ cm^6 sec^{-1}
(two body)	$\eta_2 \sim 1 \times 10^{-17}$ cm^3 sec^{-1}
Collisional detachment	$k \sim 2 \times 10^{-17}$ cm^3 sec^{-1} (ionospheric value)
	$k \sim 4 \times 10^{-20}$ cm^3 sec^{-1} (laboratory value)
Photo-detachment	$\rho S \sim 0.44$ sec^{-1}

Table I and discussions of these and other ionospheric parameters are to be found in the review articles of NICOLET and SWIDER (1963), BRANSCOMB (1964) and REID (1964). Of particular importance are the questions raised as to whether forms of oxygen serve as the dominant negative ions and whether collisional detachment really plays as strong a role in the lower ionosphere as these rate coefficients would imply.

B. RESULTS

From riometer chains established in North America and Scandinavia during the IGY, observational material on auroral absorption was obtained which has provided information on many aspects of electron precipitation in the auroral zone. These will be summarized in the following sections.

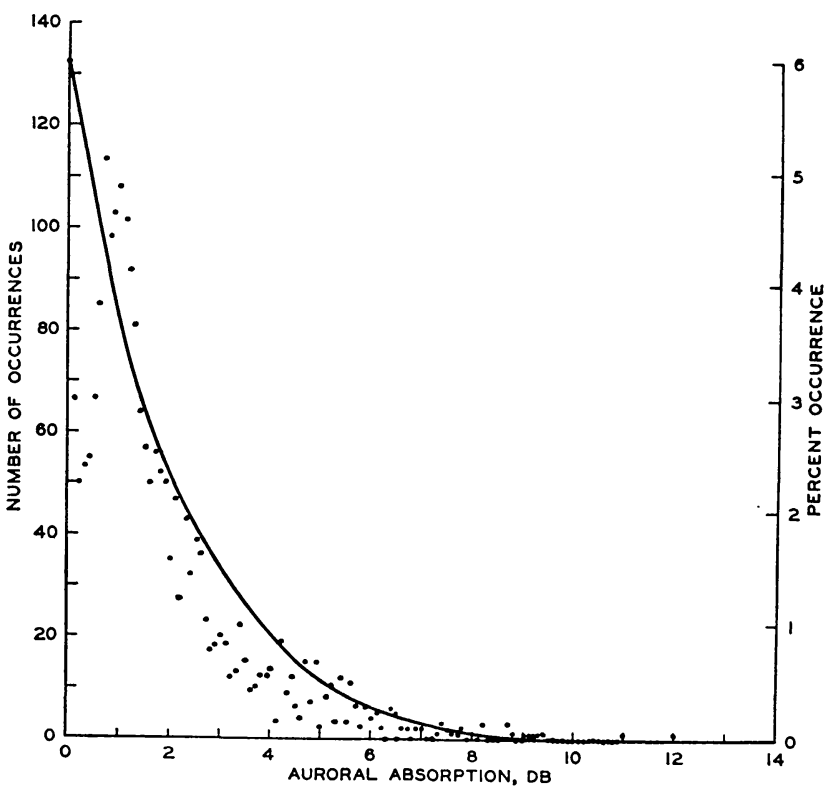

Fig. 1.1. Auroral absorption at College, Alaska, scaled at 15-minute intervals, during February 1958. (BASLER, 1963)

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1. *Magnitude of absorption*

In a recent analysis of data from the IGY riometer at College, Alaska, BASLER (1963) published a number distribution of auroral absorption values, scaled at 15-minute intervals, during an extremely disturbed month close to solar maximum. This result, given in Figure 1.1, shows that auroral absorption at 27.6 mc/s is rather modest in magnitude, seldom reaching 6 dB or so. During the period of study, absorption was less than 2 dB 63 per cent of the time, giving an indication of the typical level of auroral absorption. These features, associated with electron precipitation, are in striking contrast with the large range of absorption values found with the same riometer during PCA events in which protons and alpha particles bombard the atmosphere.

2. *Spatial distribution*

From meridional riometer chains, simultaneous recordings have been analyzed (HOLT *et al.*, 1961; HARTZ *et al.*, 1963; BASLER, 1963) for the average auroral absorption as a function of magnetic latitude. This type of analysis, or that presented in terms of percentage occurrence, indicates that auroral absorption peaks in the region which corresponds roughly to the zone of occurrence of aurora. Thus, auroral absorption events are restricted to a fairly narrow range of geomagnetic latitude, in contrast to PCA events which cover the polar cap. A comparison of the auroral absorption zone in Alaska (BASLER, 1963) with the visual auroral zone determined from all-sky camera films (DAVIS, 1962) is given in Figure 1.2; similar results were obtained by the Norwegian group (HOLT *et al.*, 1961) while the Canadian group (HARTZ *et al.*, 1963) found an absorption maximum about 1° to 2° south of the maximum observed in Alaska and Norway. This disagreement appears to result from a deficiency of the geomagnetic coordinate system.

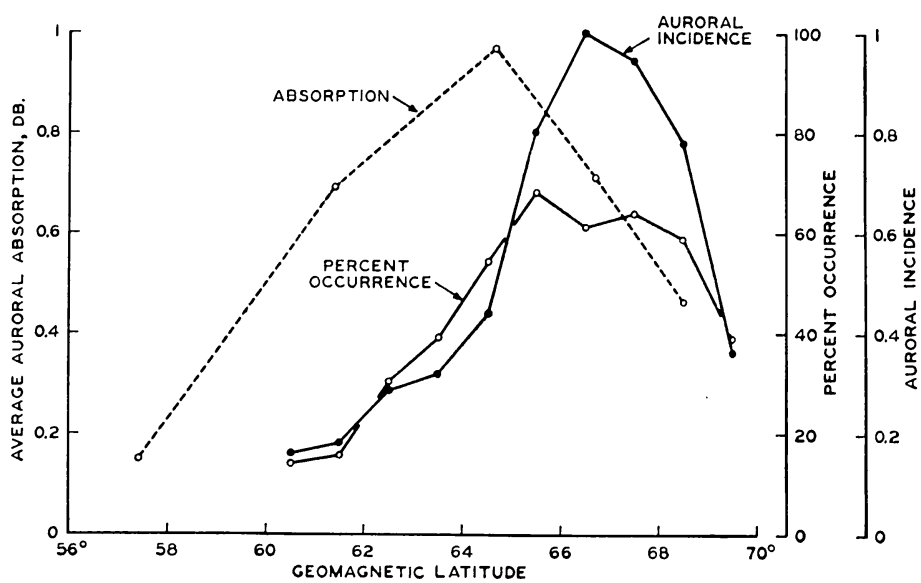

Fig. 1.2. A comparison of the auroral absorption zone in Alaska with visual auroral zones from Alaskan all-sky camera data. (BASLER, 1963.)

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Relatively little data exist on the longitude dependence of auroral absorption. However, it has been suggested that electron precipitation responsible for absorption, like that giving rise to auroral emissions, occurs simultaneously over a region which is much more extended in the E–W direction than the N–S direction. This argument, rather indirect in nature, is based on the association of both absorption and aurora with magnetic bay activity in the post-midnight hours; here, absorption recorded by riometers correlates (BARCUS and BROWN, 1962) with the position-motion features of auroral electrojets and, further, magnetic disturbance vectors (SOBOUTI, 1961; DAVIS, 1962) tend to lie perpendicular to loop arrays along which auroral forms are distributed. Thus, the picture that emerges is one in which electron precipitation, covering a wide range of energy, is controlled by the degree of solar-terrestrial interaction and is "switched on" over an extended range of longitude; the type and intensity of electron precipitation observed at a given location then depends on the local time.

These considerations, largely based on a study of auroral morphology (DAVIS, 1962) using all-sky camera films from a limited part of the auroral zone, are supported by records from more widely distributed stations. Thus, AKASOFU (1963) has examined simultaneous changes in aurora over the polar regions, finding quiet arcs extending along the whole auroral zone that is in darkness which suddenly change to more active states with the onset of polar magnetic substorms; the aurora becomes more intense, especially on the morning side but in different ways at different locations (i.e. local times). The presumption then is that this aspect of electron precipitation at low energies extends, at least a significant fraction of the time, to higher energies where ionospheric absorption and bremsstrahlung result.

While questions regarding the extent of electron precipitation, both in latitude and longitude, for a single hemisphere are of great interest, an equally important problem concerns the degree to which electron precipitation and its secondary effects are similar and simultaneous for regions in the northern and southern hemispheres connected by lines of force. Thus, conjugate aspects of electron precipitation have been examined using several different techniques. For example, HOOK (1962) compared the occurrence of "blackout" on vertical incidence ionospheric sounder records at Campbell Island, New Zealand, with auroral absorption from riometer records at Farewell, Alaska. This study indicated that strong ionospheric absorption often occurs simultaneously at nearly conjugate points; however, the mixed nature of the observational material did not permit a comparison of the intensity of absorption. Following this, LEINBACH and BASLER (1963) compared riometer records of auroral absorption events at Macquarie Island, Australia and Kotzebue, Alaska ($L \simeq 5$). This study demonstrated a high degree of correlation between conjugate points in the two hemispheres, not only for the time of absorption but also the temporal structure and the magnitude of absorption. An example of these features is given in Figure 1.3. With data from other riometers outside the immediate vicinity of the conjugate points, this study, as well as others using magnetometers (WESCOTT, 1961), showed that there are magnetically conjugate *areas*, of narrower dimensions in latitude than longitude,

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over which electron precipitation gives rise to effects of similar magnitude and structure in the two hemispheres. The lack of complete agreement, however, raised questions as to whether the disturbance phenomena are possibly non-symmetrical or the conjugate points are non-stationary in position.

For conjugate stations at higher latitudes ($L \cong 14$), HARGREAVES *et al.* (1965a) and HARGREAVES and CHIVERS (1965b), found systematic changes in the relative intensity of events in the two hemispheres, absorption tending to be greater in the winter hemisphere, and time differences between peak absorption at the two stations, the absorption peaking earlier at the place where it is larger. Thus, the conjugate relationship of auroral absorption appears to deteriorate at higher latitudes; similar results (WESCOTT and MATHER, 1964) were found with magnetic variations.

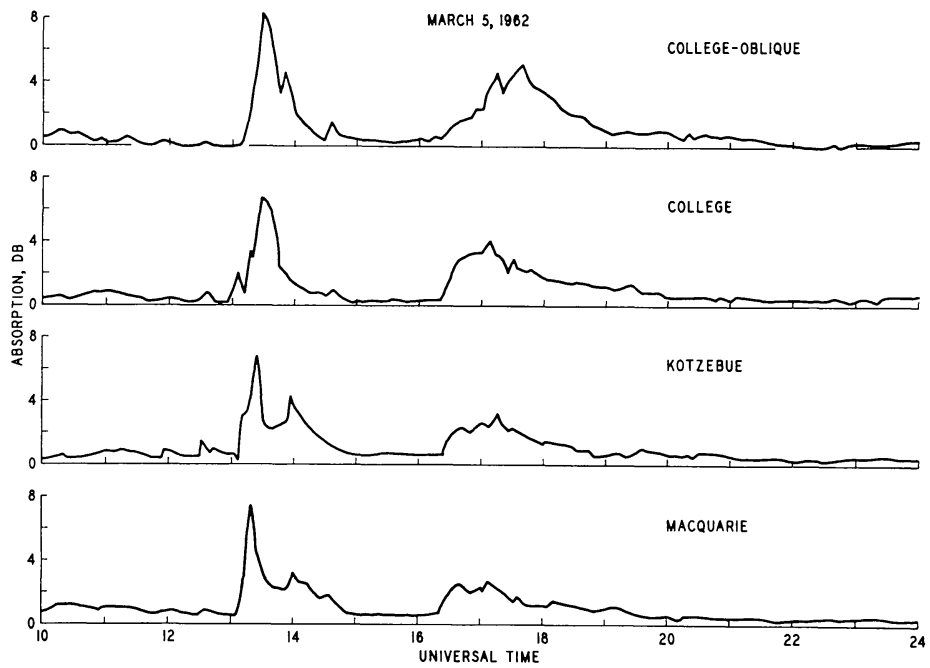

Fig. 1.3. The time variations of auroral absorption during an event recorded at three Alaskan riometer sites and one in the southern hemisphere. (LEINBACH and BASLER, 1963.)

3. *Temporal variation*

The daily variation of auroral absorption has been examined by several workers (HOLT *et al.*, 1961; HARTZ *et al.*, 1963; BASLER, 1963), using data separated according to season. By way of illustration of the results obtained, BASLER (1963) found over a five year period that absorption at College, Alaska had a pronounced maximum between 0600 and 1300 and a minimum between 1900 and 2200 local time for the winter and equinoxes; during the summer, however, the average absorption was essentially constant at all times of day. Making a further distinction between magnetically disturbed and quiet days, these same features were present, but somewhat larger in magnitude, at the different seasons; the absorption was very low and showed little daily variation during magnetically quiet days. These results are shown in Figure 1.4.

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In connection with the daily variation, it is seen that during winter and the equinoxes, auroral absorption is larger during daylight hours than at night. However, this cannot be attributed to photodetachment as the absorption maximum is not symmetrical about local noon. Another argument against photodetachment playing a strong role is that the average absorption during summer months, when solar illumination is abun-

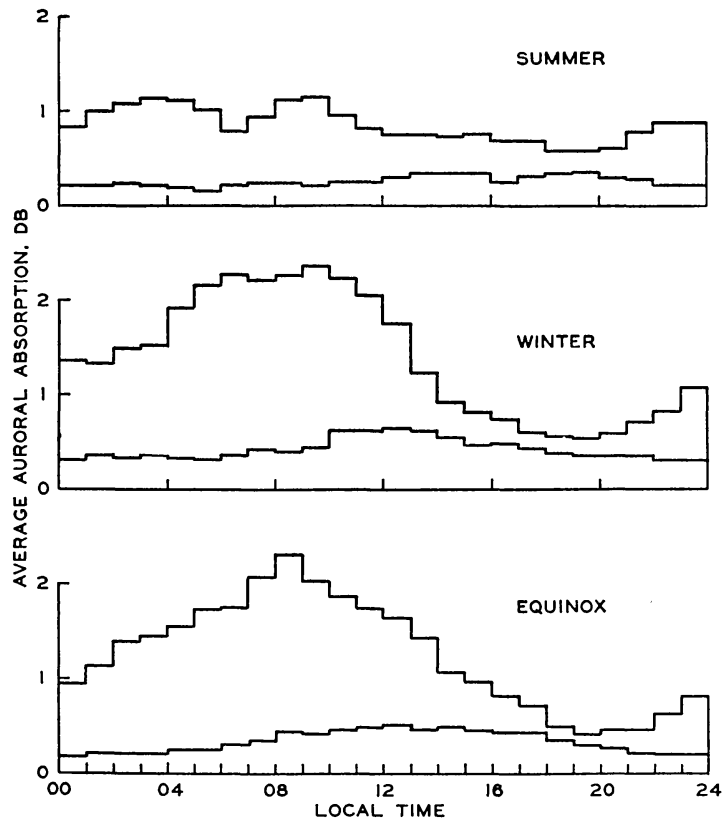

Fig. 1.4. The daily variation of auroral absorption at College, Alaska for the 5 magnetically disturbed (upper curve) and 5 quiet (lower curve) days during the period from September 1957 through August 1962. (BASLER, 1963.)

dant, is lower than during the winter. Thus, the daily variation of auroral absorption due to electron precipitation involves more than simple solar control of the absorbing region.

The difference between absorption in summer and winter months, almost a factor of two, is a seasonal feature of electron precipitation which continues fairly regularly from year to year and does not display any strong connection with solar activity. This is shown by the failure of average absorption values to decline in magnitude with the decaying phase of the present solar cycle (BASLER, 1963).

4. *Correlation with geomagnetic disturbance*

Statistical studies (HOLT *et al.*, 1961) of the dependence of auroral absorption on magnetic activity, as given by the local K index, have shown that the probability of absorption increases with increasing K index in the auroral zone. It should be noted,

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however, that there exists a class of absorption events in the auroral zone associated with little or no magnetic activity (ANSARI, 1963; HOLT, 1963; BROWN, 1964b). Riometer records of this type of event display much less in the way of time variation than those associated with magnetic activity; in addition, the local time dependences for the two types of events differ, as will be indicated below.

Looking at the correlation of auroral absorption with magnetic activity in more detail than given by 3-hour range (K) indices, it has been found that these events are associated with bay activity, especially those involving negative excursions in the horizontal component H. For simple events, absorption generally begins and ends with the growth and decay of the ionospheric current system (auroral electrojet) responsible for the negative bay and, if the current system moves to any extent in the N–S direction, the absorption reaches its largest value when the current system is

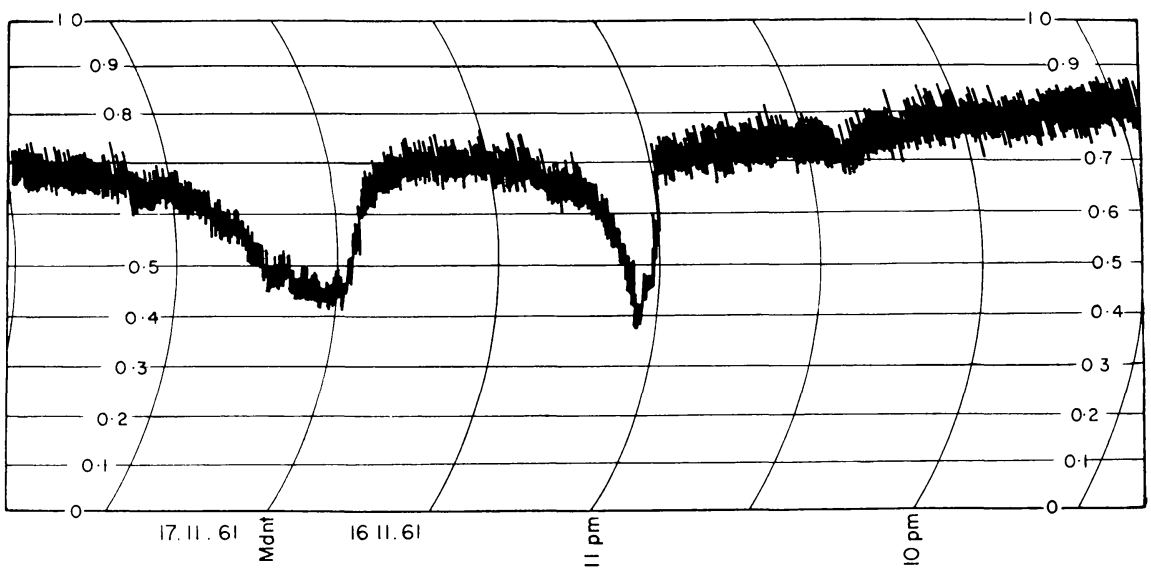

Fig. 1.5. An example of a flash-like increase in auroral absorption. (GUSTAFSSON, 1964.)

closest to the riometer site (BARCUS and BROWN, 1962). It is to be noted that this aspect of auroral absorption implies that electron precipitation occurs close to the location of ionospheric current systems. Further discussion of this feature will be given in the section on auroral X-rays.

On occasion, the development of a bay in H may be abrupt and related to the rapid breakup of quiet homogeneous auroral arcs into more active, widespread forms. This circumstance is characterized by a sudden, flash-like increase in absorption, reaching peak values in less than five minutes. Events of this type (GUSTAFSSON, 1964; PARTHASARATHY and BERKEY, 1965a), as shown in Figure 1.5, occur near the magnetic midnight meridian; bay-associated events, without the flash phase, have a similar time distribution but extend somewhat further into the morning hours.

During storm conditions, when magnetic disturbances are complex, the simple considerations given above in connection with isolated bays are difficult, if not

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impossible, to apply. With magnetic disturbances being recorded over a wider range of latitude and bays overlapping in time, the number of electrojet-precipitation regions must be large and have complex space-time histories. Absorption under these conditions is more intense, highly structured in time and of greater duration.

In connection with the association of absorption with strong magnetic activity, it is to be noted that magnetic storms are classified according to whether their onset is gradual or sudden. It is the second category (SC) that is of particular interest as

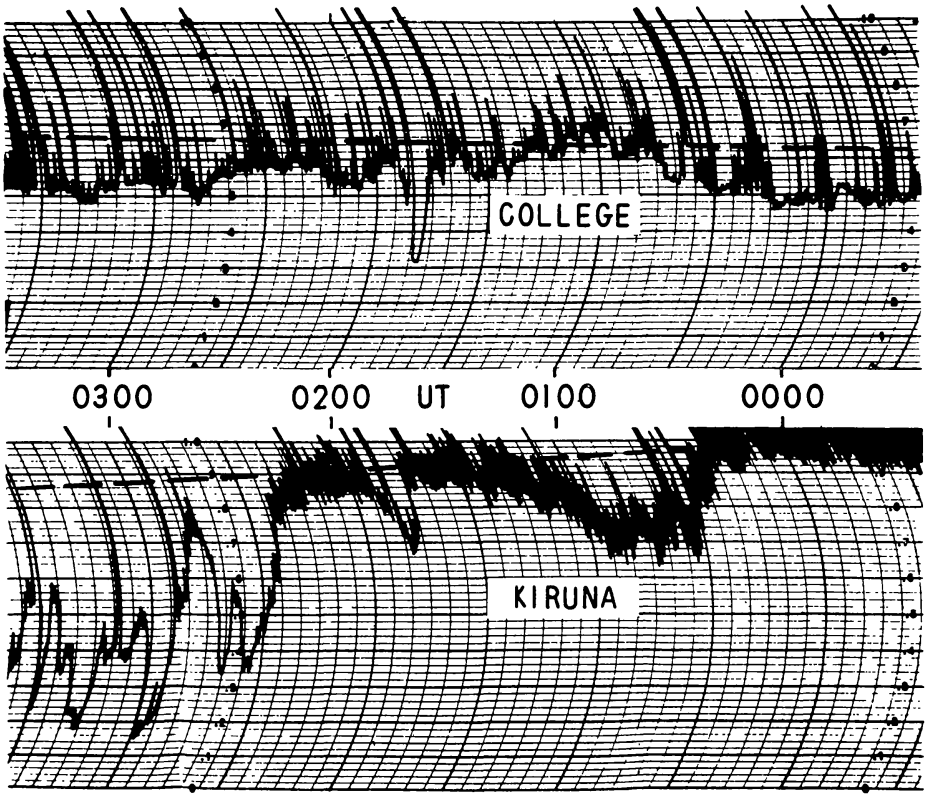

Fig. 1.6. An example of ionospheric absorption at the onset of a sudden commencement magnetic storm; June 27, 1960. (BROWN *et al.*, 1961.)

observations (BROWN *et al.*, 1961) indicate that brief, but significant increases in absorption occur with the sudden commencement. While X-ray data (ANDERSON, 1958; BROWN *et al.*, 1961; HOFFMAN and WINCKLER, 1963; KEPPLER *et al.*, 1962) from balloon flights indicate that this results from intense bursts of electrons, these observations are relatively few in number and limited to individual auroral latitude sites. Riometers, on the other hand, have provided a large number of cases and because of their locations indicate something of the geographical distribution of electron precipitation with the onset of an SC.

An example, where increased absorption was recorded over Alaska and Sweden with the onset of an SC, is given for the storm starting at 0146 UT on June 27, 1960, as shown in Figure 1.6. Using observational material from a period of $2^1/_2$ years, from July 1958 to December 1960, riometer records from Alaska, Canada and Scandinavia

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were examined (ORTNER *et al.*, 1962) for similar features at the sudden commencements of 71 storms. Excluding cases where the riometer records, for five-minute periods before and after the SC's, were contaminated by other types of absorption already in progress, at least 25 (and quite probably more than 50) of the 71 SC's showed increases in absorption at auroral latitudes. These were found to be simultaneous with the SC and lasting about 5 minutes. This type of absorption occurred on the day as well as the night side of the earth, limited largely to auroral latitudes but extending in a patchy, ring-like region around the polar cap. HARTZ *et al.* (1963) have shown that the probability of observing sudden commencement absorption (SCA) is greatest at local noon, falling off in about the same manner for times earlier or later. Additional features of the electron precipitation accompanying SC's are found in balloon X-ray data and auroral radar echoes; the balloon data provide estimates of the electron fluxes after an SC while radar observations (UNWIN and BROOKS, private communication) show space and time variations of the ionization that results from the electron bombardment.

Another distinctive aspect of magnetic activity with which absorption due to electron precipitation has been identified is the giant pulsations ($\sim 100\,\gamma$) at auroral

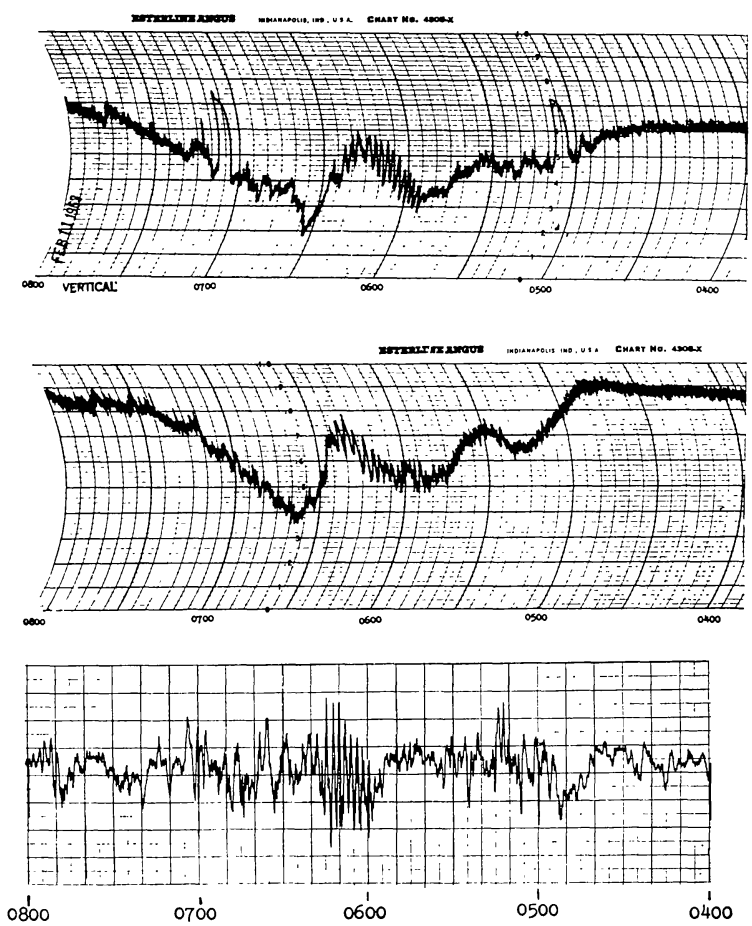

Fig. 1.7. An example of pulsating absorption at College (top) and Healy (middle), Alaska, separated by about one degree in latitude, and simultaneous variations in earth current (bottom). (PARTHASARATHY and HESSLER, 1964.)

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latitudes. These magnetic pulsations occasionally occur around the dawn and dusk meridians, with the dawn pulsations larger in amplitude (NAGATA, 1963). Absorption pulsations are found (ZIAUDDIN, 1960; ANGER *et al.*, 1963; BROWN, 1964; PARTHASARATHY and HESSLER, 1964) to accompany *some* of the magnetic pulsation events in the morning hours, as shown in Figure 1.7, but to date only a very few instances of pulsating absorption has been found in the evening hours.

At auroral latitudes, these pulsating absorption events often have durations from 45 to 150 minutes, the time between pulsations range from 150 to 500 seconds with an average around 360 seconds; however, there is no peak-for-peak correlation between the magnetic and absorption pulsations. The amplitude of pulsations in absorption varies during events but it can reach 2 dB or so on occasion.

The time distribution for the occurrence of pulsating absorption is similar to slowly varying absorption events which take place without significant magnetic activity (BROWN, 1964); however, the K_p range for pulsating events is somewhat higher ($K_p \geqslant 4$) than the slowly varying events ($K_p = 2$–4). This suggests that pulsating and slowly varying events are related, the pulsations resulting when slowly varying precipitation events undergo modulation associated with the higher level of magnetic activity.

X-ray data from balloon observations (ANGER *et al.*, 1963; BARCUS and ROSENBERG, 1965) during events of this type as well as multi-station riometer data, indicate that the spatial structure of electron precipitation associated with giant pulsations is limited in latitude; in addition, it is distributed along the auroral zone. Auroral radar data (KEYS, 1965) show "diffuse" pulsating echoes at these latitudes and with periods in the same range.

Examples of long-period pulsating events occurring at the same time in conjugate regions of the auroral zone have been noted (CHIVERS and HARGREAVES, 1964; BROWN *et al.*, 1965). The number of events is relatively few but indicate general similarities in the two hemispheres.

Finally, as indicated at the beginning of this section, there is the class of absorption events noted for a conspicious absence of simultaneous magnetic activity. These are slowly varying in time, appearing deceptively like polar cap absorption events, and have a time distribution (BROWN, 1964b) peaking around the dawn meridian. The resemblance to PCA events led to the suggestion (HOLT, 1963; ANSARI, 1963) that proton bombardment of the atmosphere was responsible for the absorption at these times; however, these events show little change in absorption with and without solar illumination (BROWN, 1964b), suggesting that higher portions of the ionosphere are involved, and balloon studies (BROWN and BARCUS, 1962) have shown bremsstrahlung fluxes associated with the absorption events.

5. *Correlation with aurora*

In studies of the relation between ionospheric absorption at auroral latitudes and the occurrence of visual aurora, experimental techniques have varied considerably. Thus, early work (HEPPNER *et al.*, 1952) compared ionosonde "blackouts" with visual

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observations while other efforts involved riometer observations and all-sky camera films (HOLT *et al.*, 1961), showing the location of aurora relative to the riometer antenna pattern; or riometer and photometer observations (HOLT and OMHOLT, 1962; GUSTAFSSON, 1964; JOHANSEN, 1964), with dissimilar angular beams; or ionospheric absorption with the luminosity over the riometer antenna pattern (BROWN and BARCUS, 1964), using the transmission of all-sky camera films; or narrow-beam riometer and photometer observations (ANSARI, 1964), covering essentially the same regions of the sky.

The results of thise studies have shown that absorption is associated with the occurrence of aurora but the closeness of the correlation depends on the phase of the aurora as well as the experimental technique employed. Generally speaking, the absorption associated with quiet forms in the riometer antenna pattern is not very large in magnitude nor rapid in its time variations. With the rapid growth of luminosity and activity of these forms at breakup, absorption increases and shows more marked time variations. With breakup and the time that follows, the aurora is associated with westward electrojets which give rise to negative magnetic bays.

By way of summary, HEPPNER *et al.* (1952) found a strong connection between ionosonde "blackouts" and the occurrence of pulsating and flaming aurora; HOLT *et al.* (1961), comparing absorption recorded by five riometers in a close arrangement at the northern tip of Norway, found that ionospheric absorption increased when

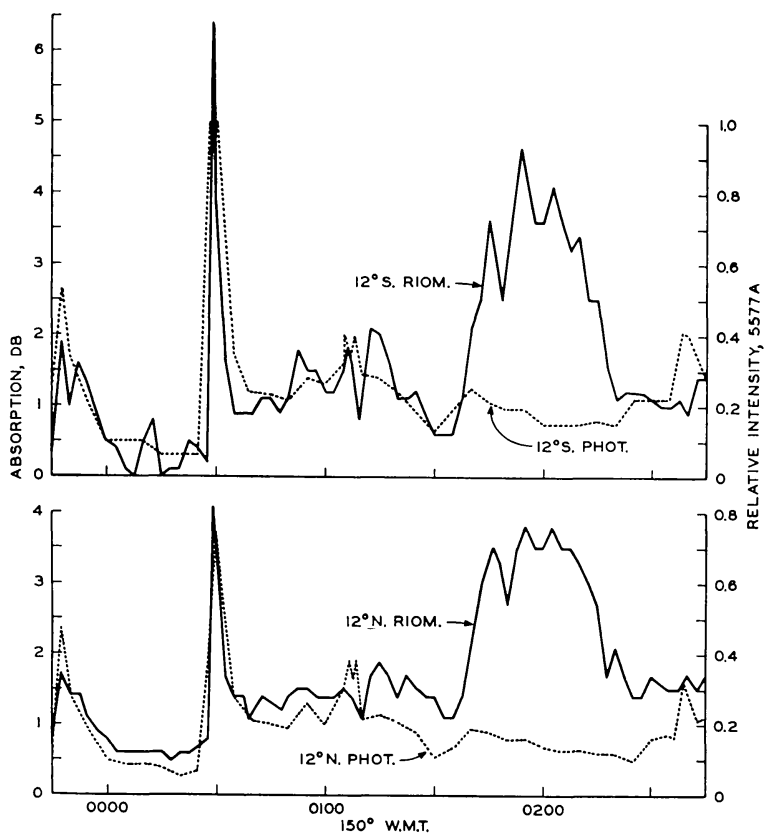

Fig. 1.8. Variations in ionospheric absorption and relative 5577 Å intensity measured during an auroral event by riometers and photometers directed 12° N and S of College, Alaska. (ANSARI, 1964.)

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aurora was present over the riometer stations; HOLT and OMHOLT (1962), comparing absorption recorded by a riometer with a broad-beam antenna and a narrow (5°) beam photometer for 5577 Å, found correlation between riometer and photometer records but the correlation was the best when the aurora covered the riometer pattern and the poorest with distinct, isolated forms; BROWN and BARCUS (1964), examining luminosity changes given by the transmission of all-sky camera records over a broad-beam riometer antenna pattern in the post breakup phase of aurora, found a strong variability in the correlation between luminosity and absorption; ANSARI (1964), using 5577 Å photometers and a 36 mc/s riometer with comparable beam widths, found that ionospheric absorption associated with aurora falls into two main categories: one, near local midnight, correlates well with intensity fluctuations of 5577 Å and is limited to luminous regions of the sky while the other is observed only in the post-midnight hours and does not correlate well with intensity variations of 5577 Å and most likely is not limited to luminous regions of the sky; in addition, with the transition from the first to the second category, a ten-to-hundred fold increase takes place in the ratio of ionospheric absorption to 5577 Å intensity. This is illustrated by Figure 1.8 where variations in absorption and relative 5577 Å intensity that occurred during an auroral event are shown.

On a faster time scale, variations of ionospheric absorption have been shown (CAMPBELL and LEINBACH, 1961; CAMPBELL and REES, 1961) to be closely related to

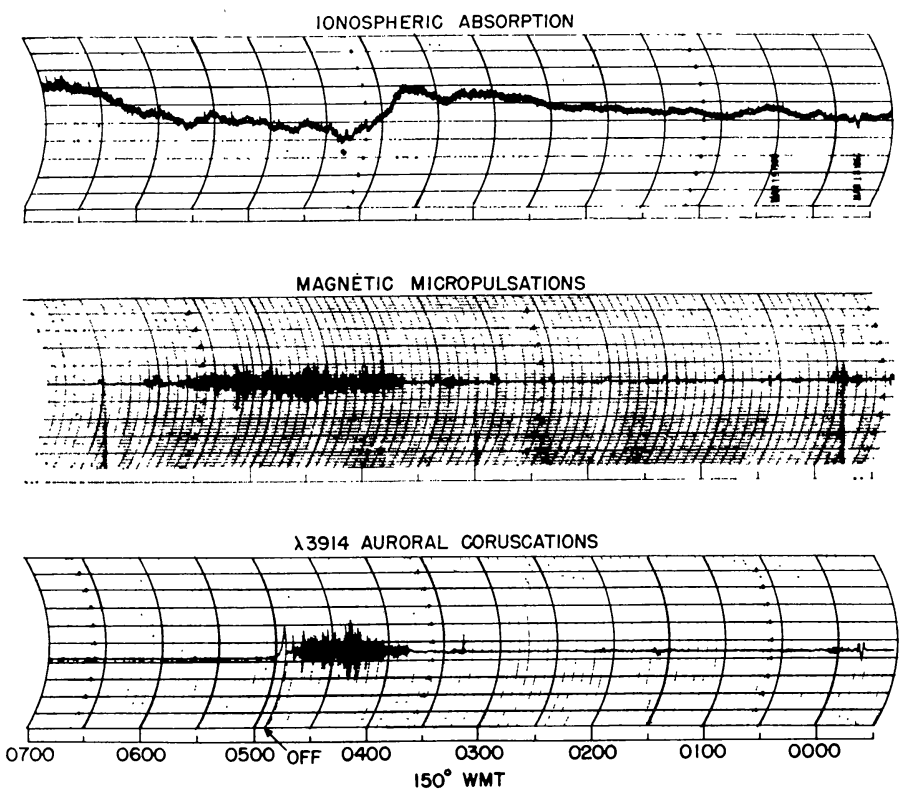

Fig. 1.9. An example of simultaneous ionospheric absorption, magnetic micropulsations and auroral coruscations. (CAMPBELL and LEINBACH, 1961.)

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magnetic field micropulsations and short period coruscations of 3914 Å as shown by the example in Figure 1.9.

6. *Height of the auroral absorbing layer*

With the knowledge that absorption due to electron precipitation is found localized close to the visual auroral zone and that, at times, it is associated with features of the aurora and ionospheric current systems, it is of interest to examine the height of the ionization responsible for the absorption and to compare it with the heights of auroral forms and electrojets. In this connection, statistical studies, as summarized in RATCLIFFE (1960), show that the distribution in altitude of lower borders of auroras peaks at about 105 km and extends from 90 km to 125 km; the ionospheric current systems responsible for magnetic bay disturbances are generally considered to flow at these same altitudes. On the other hand, the auroral absorption region is somewhat lower in the atmosphere than these regions, indicating that more energetic electrons

TABLE II

Range and penetration depths of energetic electrons in the atmosphere

Energy keV	Range (gm/cm^2)	Max. penetration (km)
10	2.85×10^{-4}	98.5
30	1.99×10^{-3}	88.0
50	4.90×10^{-3}	83.5
70	8.80×10^{-3}	80.5
100	1.62×10^{-2}	77.5
200	5.07×10^{-2}	71.0
300	9.52×10^{-2}	67.0
400	1.46×10^{-1}	64.0

are involved. To place the subsequent discussion in proper perspective, the range (in gm/cm^2) and maximum penetration depths in (kilometers) for electrons of various energies are given in Table II; these ranges were obtained by SPENCER (1955) and the corresponding depths are based on the ARDC Model Atmosphere in the *Handbook of Geophysics* (1960).

Efforts to locate the ionization during auroral absorption events have involved several methods. The simplest, and obvious first step, was to look at the day-night ratio of auroral absorption, as suggested by results found during polar cap absorption events. Here, it was noted that during solar cosmic ray bombardment the nighttime absorption values were, on the average, one-fifth of the daytime values for the same particle flux on the atmosphere. This indicates that polar cap absorption takes place in a region where negative ions (e.g., O_2^-) play an important role and, when illuminated by the solar spectrum, undergo photo-detachment and thus release electrons which add to the absorption. With ionospheric rate coefficients generally used in recent times, summarized in Table I, this places the peak electron density during PCA events around the 70 km level.

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While studies of the day-night ratio of auroral absorption events yielded conflicting results at first, HOLT *et al.* (1961) reporting a ratio close to the value characteristic of PCA events, more recent results place it lower; for example, HOLT (1963) gave a revised day-night ratio of 2 for a limited amount of data, HULTQVIST (1962) reported a value of approximately 1.25 during equinoxes from 1958 to 1961, BROWN and BARCUS (1963) reported a ratio of unity for absorption events associated with negative bays, BROWN (1964) noted a ratio of unity for auroral breakup events and BROWN

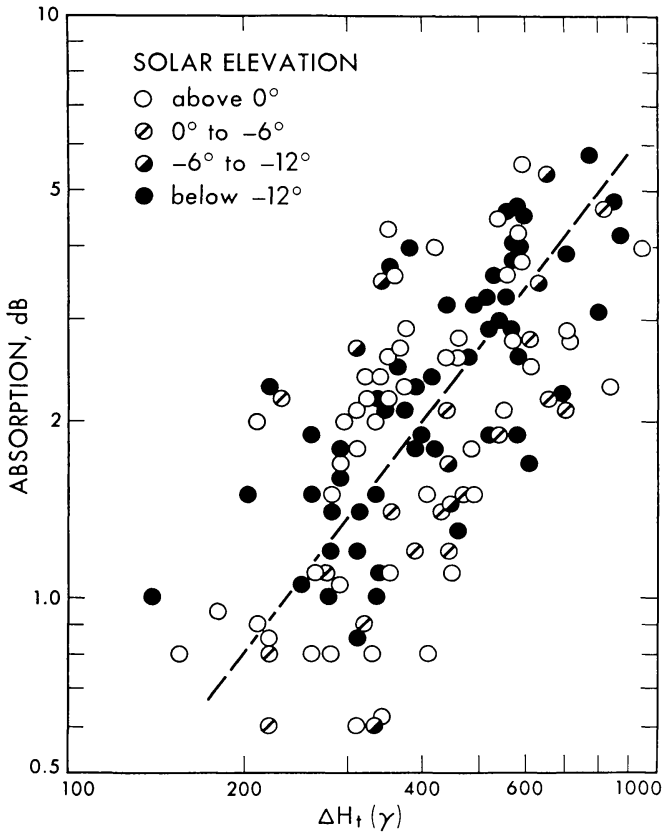

Fig. 1.10. Auroral absorption (27.6 mc/s) for different solar elevation angles as a function of horizontal magnetic disturbance. (BROWN and BARCUS, 1963.)

(1964), using a limited amount of data for slowly varying absorption events, found a day-night ratio of 1.27.

Features of this type of observational material are illustrated by Figure 1.10 (BROWN and BARCUS, 1963) which shows auroral absorption as a function of horizontal magnetic disturbance for different solar elevation angles. In this study, the events were selected primarily according to the magnetic circumstances; only slowly varying negative bay events were used for which the current systems were located over the riometer site. With this criterion, no distinction was evident between daytime and nighttime absorption events.

It should be noted that these studies were made at geographical latitudes in the range from 65° to 70°. Consequently, the day and night absorption values were from

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times around dawn and dusk during the equinoxes (HOLT *et al.*, 1961; HOLT, 1963; HULTQVIST, 1963) or around local midnight during summer and winter (BROWN and BARCUS, 1963; BROWN, 1964a). Since riometer data from an auroral station near either of the geographic poles has not been available, a day-night absorption ratio for auroral events around local noon has not been determined. In view of the distinction between absorption events around midnight associated with bay disturbances and events in the morning hours which occur in the absence of geomagnetic activity, these day-night absorption studies deal with different aspects of electron precipitation in the auroral zone. It would be an important addition if such studies could be extended into the hours closer to local noon; this is particularly true in view of the daytime maximum in absorption as well as the different type of magnetic activity (and possibly precipitation) at this time.

These results, in contrast to those for PCA events, suggest that auroral absorption is located at heights where negative ions play a minor role, at least for local times from about midnight to the dawn meridian. It cannot be said that this approach gives a measurement of the height of the auroral absorption layer but it places the absorption region where electrons produced by the incoming flux recombine with positive ions rather than undergo attachment with neutral constituents and produce negative ions. For the coefficients outlined in Table I, this would put the ionization around the 90 km level or so, somewhat below the levels generally associated with auroral displays and electrojets. Electrons penetrating vertically to this depth have energies $\gtrsim 30$ keV; for other directions, the energies are somewhat higher.

Since single-frequency riometer data does not give *direct* information as to the height at which ionization causing auroral absorption is located, multi-frequency riometer observations, taken on widely spaced frequencies, have been used to infer electron density profiles during these events. This method depends on the fact that the ratio of absorption observed on different frequencies is a function of the ratio of the electron-neutral collision frequency ν in the absorbing region to the angular radio frequency ω. Thus, when the absorbing region is located at great heights, where the collision frequency ν is small compared to the angular frequency ω, inverse-square-dependence for the absorption as a function of frequency results. On the other hand, when the absorbing region is located at low heights, the collision frequency ν is large compared to the angular frequency ω and makes the absorption independent of frequency. Using the collision frequency profile based on the work of KANE (1961), the dividing point ($\omega = \nu$) for a frequency of 30 mc/s is at 60 km.

Writing absorption as a power law in the form

$$A(f_e) = C f_e^{-n}$$

the exponent n ranges between 2 and zero for the two extremes of great and low heights of the absorbing region, respectively. In this representation, f_e is the effective frequency

$$f_e = f \pm f_L$$

where f is the radio frequency and f_L is the electron gyrofrequency corresponding to

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the longitudinal (vertical) component of the geomagnetic field. In making comparisons at different frequencies, it is important that the various riometer antenna patterns view the same region of the sky. In addition, it should be noted that non-uniform distributions of ionization across (horizontally) the antenna pattern systematically lower the exponent n.

Using this technique at College, Alaska, with riometer frequencies extending from 10 to 50 mc/s, LERFALD *et al.* (1964) examined the frequency dependence of

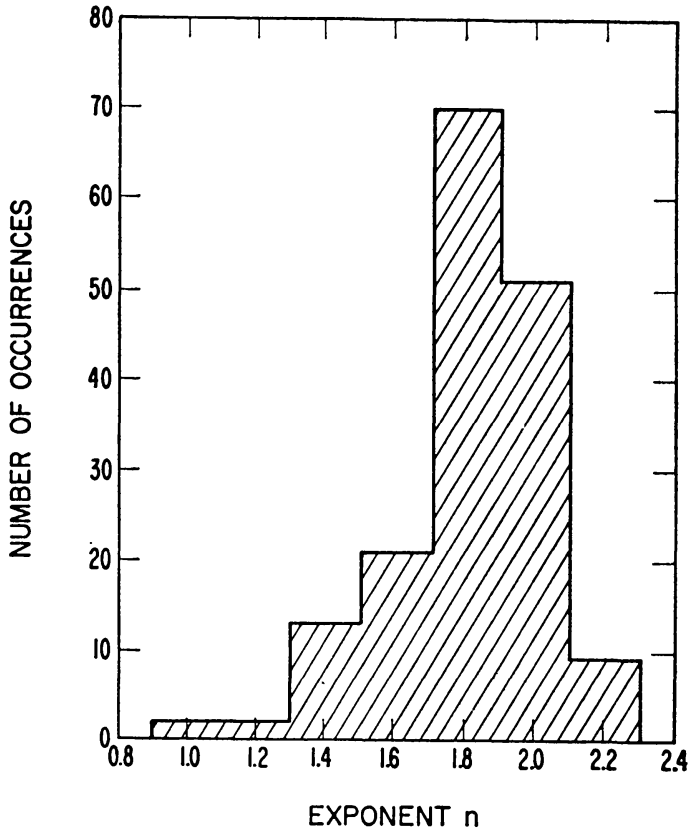

Fig. 1.11. The occurrence distribution of the exponent n in the frequency dependence of auroral absorption. (LERFALD *et al.*, 1964.)

auroral absorption events from November 1961 to December 1962. For 168 absorption values in 65 different events, the occurrence distribution of the exponent n was found to peak at 1.8 ± 0.1, as shown in Figure 1.11; approximately 36 per cent of the observations were characterized by $n = 2.0 \pm 0.1$, corresponding to the case where the absorbing region was located at "great heights", and 78 per cent of the events had $n \geqslant 1.8 \pm 0.1$. A scatter plot of exponent n versus absorption shows that low values of n (low heights) appeared primarily for weak absorption events. In addition, this study showed that the exponent n was lower for daytime events than those at nighttime, suggesting that daytime events are characterized by a flatter energy spectrum and thus more influenced by photo-detachment.

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These observations have been fitted by cubic electron density profiles; these, in turn, give incremental absorption profiles at 20 mc/s (extraordinary mode) peaking at 70 km or above for almost 80 per cent of the sample. Since the increase in electron collision frequency with decreasing altitudes has the effect of peaking the incremental absorption at lower altitudes than the electron density profile, the main ionization lies above this region.

Absorption events were used in this study without classifying them according to type. PARTHASARATHY and BERKEY (1965a) sorted out events showing a fast, flash-like onset of absorption, typical of the midnight breakup phase of quiet auroral forms as well as slow, smoothly varying events (PARTHASARATHY and BERKEY, 1965b) characteristic of the dawn breakup phase of auroras. For both types of events from more limited data, the average value of n was about 1.5. The midnight events are undoubtedly less wide-spread in extent, at least in latitude, than the morning events; thus, while the two exponents are essentially the same, their interpretations are quite different as far as electron spectra are concerned.

Another approach to finding the location of the absorbing region during auroral events involves carrying out radio propagation experiments based on the reception of signals transmitted from the ground to rocket-borne receivers. From the relative amplitudes of signals as well as the phase relationship between signals of different frequencies, this method gives the electron density N and the collision frequency ν as functions of height. Similar results have also been obtained by simple Faraday rota-

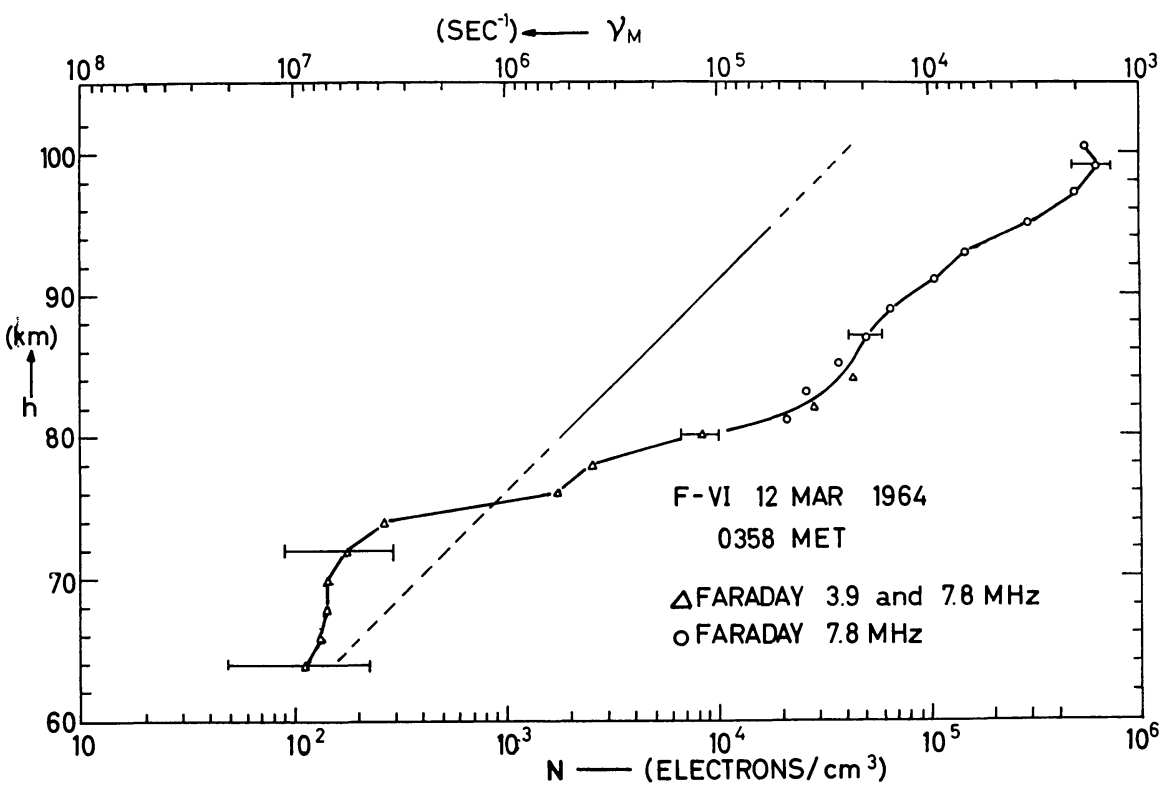

Fig. 1.12. Electron density observations during a 1.5 dB absorption event at 27.6 mc/s. (LANDMARK, 1964.)

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tion experiments in which linearly polarized waves transmitted from the ground are received on similarly polarized antennas on the rocket.

An example of the results (LANDMARK, 1965) obtained by this last technique is shown in Figure 1.12, indicating a peak electron density close to 10^6 electrons/cm^3 at the 100 km level during a 1.5 dB absorption event on a 27.6 mc/s riometer. For this event, most of the ionospheric absorption occurred well above the 80 km level and peaked around 98 km. Other electron density profiles observed during auroral absorption events, normalized to unit electron density at 80 km, are shown in Figure 1.13. The difference for day and nighttime results below 80 km is due to photodetachment of electrons from negative ions during daytime. These profiles indicate

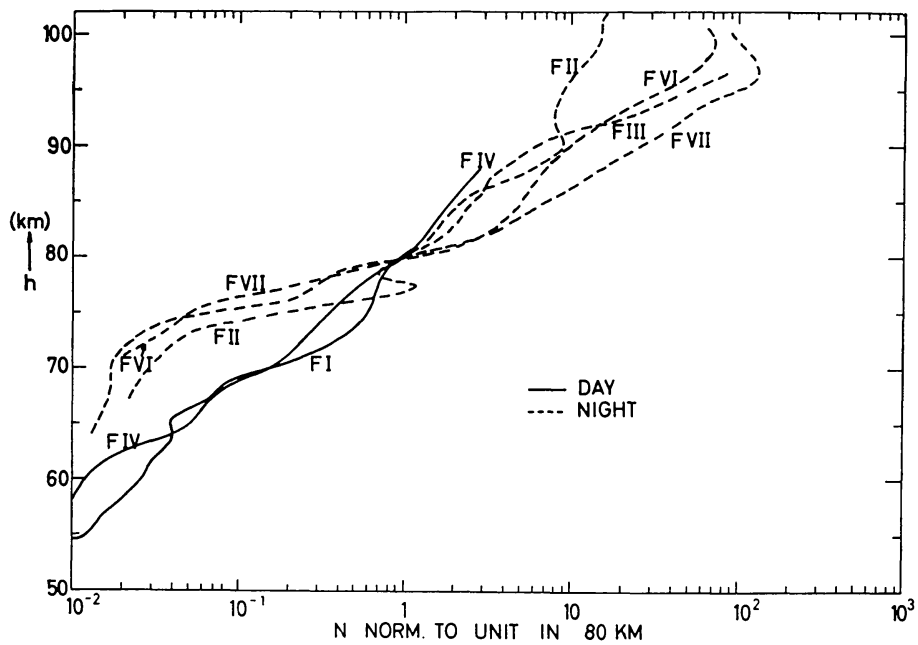

Fig. 1.13. Electron density profiles observed during auroral absorption events, normalized to unit electron density at 80 km. (LANDMARK, 1964.)

that auroral absorption occurs at fairly high levels, resulting from incoming electron fluxes with fairly steep energy spectra.

Theoretical estimates have been made of the electron density profile during auroral absorption events using different spectra for the incident electrons. Thus, PEDERSEN (1960) and POPOFF and WHITTEN (1963) used power-law spectra deduced from X-ray observations (ANDERSON, 1960) within the atmosphere while BROWN (1964) used both power-law and exponential spectra with energy inputs comparable to those found (CHAMBERLAIN, 1958) in auroras. In these calculations, PEDERSEN (1961) used the range-energy and ionization loss relations appropriate for electrons while the calculations of POPOFF and WHITTEN (1963) and BROWN (1964c) relied on the energy deposition functions developed by SPENCER (1959). These approaches yielded peak electron densities at the 90–100 km level, assuming the electrons precipitating on the atmosphere to arrive essentially along the field lines. Vertical absorption values from

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these calculations are applicable to circumstances where the ionization is uniform over a wide range of latitude and the implications were that the electron spectra would have to be quite steep so as not to yield absorption values beyond the range of auroral events (BASLER, 1964) or day-night absorption ratios (BARCUS and BROWN, 1962) much above unity. More limited latitude distributions of ionization were not considered.

HULTQVIST (1964a, b) has carried out similar calculations using both steep electron spectra, as found by MCILWAIN (1960) during an auroral rocket flight, and flatter spectra, found by MANN *et al.* (1963) on a polar satellite during magnetic storm conditions. In this work, an empirical relation (MAEDA, 1963) was used for the electron attenuation in the atmosphere and the steep electron spectrum was assumed isotropic over the upper hemisphere while the flatter spectrum was limited to a solid angle of one steradian around the field lines. The energy input used for the steep spectrum was comparable to that found in visual auroral events (IBC 1 or so) while the energy input for the flatter spectrum was so low as to be beyond detection. By combining these spectral types, it was pointed out that aurora without appreciable absorption as well as strong absorption without appreciable visual aurora could be expected. Since the flat spectrum places the ionization by incident electrons at heights in the 60–90 km range, HULTQVIST (1964a, b) argued that the negative ion-electron density profiles of NICOLET and AIKIN (1960) and others are incorrect in view of the observed day-night absorption ratio around unity for auroral events.

Recently, REES (1964) has examined the luminosity profile of auroral forms for isotropic angular distributions of electrons incident on the atmosphere. Relatively good agreement was obtained using modified exponential spectra (e.g. $\mathrm{d}N/\mathrm{d}E \sim E \exp(-E/E_0)$) together with an isotropic form of Spencer's energy deposition function based on GRÜN's (1957) experimental results. As yet, a detailed discussion of the results obtained with this form of dissipation function has not been given for the higher energy portion of the electron spectrum responsible for auroral absorption; however, individual calculations have been reported (MCDIARMID and BUDZINSKI, 1964) in which a single spectrum was used and absorption calculated for both day and night conditions of the ionosphere.

C. DISCUSSION

From ionospheric absorption records at auroral latitudes, not only qualitative information bearing on spatial and temporal aspects of electron precipitation have been developed but also quantitative results such as the magnitudes of absorption at a particular frequency ($\sim$30 mc/s) during a variety of events. The interpretation of these features depends on properties of the incident beam as well as the ionosphere. Early in the development of this field, as in the PCA problem, the question of the location of the auroral absorption region was raised; that is to say, is ionospheric absorption (typically 1 dB or so at 30 mc/s) during electron precipitation events due to large electron densities (10^5–10^6 electrons/cm^3) at high altitudes ($\gtrsim$90 km) or small electron densities (10^3–10^4 electrons/cm^3 at low altitudes ($\lesssim$70 km)?

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In considering the results of riometer studies bearing on this question, it is important to note that the observational method is essentially the same as used in connection with PCA events. However, the particle bombardment of the atmosphere giving rise to polar cap absorption is vastly different from that in auroral absorption events. Thus, PCA events involve heavy particles in the MeV energy range which cover the whole polar cap while auroral absorption events result from electrons in the keV range which are restricted to a narrow range in latitude; further, solar cosmic ray bombardment varies slowly with time whereas auroral absorption events display rapid time variations and position-motion effects associated with ionospheric current systems.

Since the particle bombardment responsible for PCA events is so widespread compared to the horizontal extent of a riometer antenna pattern, the analysis and interpretation of absorption data has not been hampered by geometrical considerations other than those associated with the polar diagrams of antenna patterns. However, features of auroral absorption events indicate a more limited extent to electron precipitation and thus it is important to consider geometrical aspects of the particle influx relative to riometer antenna patterns, especially in attempting to infer features of the incoming electrons. This may be illustrated by considering aspects of auroral absorption, other than morphological features, which are related to the energy spectra of electrons: (1) magnitude, (2) day-night ratio and (3) frequency dependence of absorption.

From the work of Ansari (1964), using an antenna array with several narrow beams, it is evident that ionization is frequently distributed over the sky in an irregular patchy manner; thus, the range of absorption values reported by Basler (1963) represent lower limits of the actual absorption within the region of ionization. By this same token, absorption values from riometers and broad-beam antennas underestimate the electron density and effectively place the absorption region at lower heights, where the collision frequency is greater, to account for the absorption.

Similar considerations would apply to the individual absorption values used in examining the day-night ratio of auroral absorption although it is not clear from the information now in hand to what extent the day-night ratio is affected. For the actual absorption ratio to differ from values already obtained would require a significant difference in the geometry of daytime and nighttime absorption events. In the case of those events near local midnight (Brown and Barcus, 1962; Brown, 1964), a seasonal effect would be necessary, making events in the summer significantly different from those in winter. Thus, the day-night ratio would appear to be lower than it actually is if summer precipitation events were less intense or narrower in extent than those in winter. At the equinoxes (Hultqvist, 1963; Brown, 1964b), where the day-night ratio is obtained from absorption values near dawn and dusk, there seems little chance of geometry affecting the ratio as absorption shows a strong minimum in the early evening hours, thus making the values from around dawn the principal source of data.

With multi-frequency riometer studies, non-uniformity of ionization is important even though great care is taken to make the antenna patterns the same on the various

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frequencies. Thus, LERFALD *et al.* (1964) have indicated that a horizontal gradient in ionization, amounting to a factor of two across the antenna beam width, may depress the exponent n in the frequency dependence of auroral absorption by 0.1. It would seem that sharper gradients are often possible and thus depress the exponent n even more, particularly for the flash-like events around the midnight breakup period (PARTHASARATHY and BERKEY, 1965a). For example, a 1 dB event at 30 mc/s, actually covering only 7/8ths of the antenna pattern with ionization at "great heights", would give 6.9 dB at 10 mc/s; instead of an n value of 2, appropriate to ionization in the upper reaches of the D-region, a value of $n=1.75$ would result from the frequency dependence of absorption. Similarly, if only 3/4ths of the antenna were covered, an exponent of $n=1.55$ would be obtained. As a result, the limited spatial extent of auroral events suggests that ionospheric techniques underestimate the height of the auroral absorption region or, equivalently, overestimate the contribution of high energy electrons in the incident flux.

In addition to collision processes of the incident electrons, ionization is formed by the absorption of bremsstrahlung X-rays by atmospheric constituents. While this represents a relatively inefficient source of ionization, the photons propagate downward, deep into the atmosphere, and are absorbed at levels where the specific absorption (dB/km) is considerably larger than in the collision ionization region. As a result, it might be expected (CHAPMAN and LITTLE, 1957) that auroral absorption would show less spatial structure than the incident electrons as well as a significant effect due to photo-detachment of the ionization at lower levels where negative ions play an important role in ionospheric processes. Studies of the day-night absorption ratio do not show this, however; in addition, calculations (ANSARI, 1963; BROWN, 1964c), using recent estimates of ionospheric rate coefficients, suggest that bremsstrahlung is responsible for only a small portion of the absorption, even for relatively high energy (>100 keV) electrons incident on the atmosphere. In essence, these studies show that collision ionization is confined to high altitudes where the effective recombination coefficient is relatively constant whereas X-ray ionization is distributed over a fairly broad region where the effective recombination coefficient varies by about six orders of magnitude; thus the electron production rate profile controls the ionization at high altitudes, moving downward into regions of increasing collision frequency with increasing electron energy, while the effective recombination rate controls the ionization profile at lower altitudes, keeping it relatively fixed in position but increasing slowly with increasing energy. This indicates that absorption due to collision ionization grows faster with energy than that due to the absorption of bremsstrahlung and dominates the situation. These calculations, while apparently confirming the lack of a day-night absorption ratio, were obtained with fairly rudimentary approximations for the bremsstrahlung cross section and geometrical aspects of the problem.

While the inefficient bremsstrahlung process places a small amount of ionization deep in the atmosphere, thus giving a fraction of auroral absorption which may be influenced by photo-detachment, the lack of a large day-night ratio argues strongly

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against ionization by direct penetration of energetic (>100 keV) electrons to deep ($h<80$ km) levels of the atmosphere. More direct support of this comes from X-ray observations at balloon altitude where it has been found that the photon spectrum is relatively soft with only small, infrequent fluxes above 100 keV.

Summing up, the interpretation of auroral absorption depends on the properties of the incoming electron beam (e.g. flux, spectra, angular and spatial distributions) and the atmosphere (e.g. composition, ionic constituents and reaction rate coefficients). Both aspects of the problem have uncertainties in them. Since it is now established (as discussed in the subsequent parts of this paper) that the particle beam shows wide variations in its parameters, further progress in untangling these results will most likely follow when the lower ionosphere, which is more stable in its properties, is better understood.

2. X-ray Studies

Another aspect of electron precipitation at auroral latitudes, besides ionization produced by collision processes with atmospheric constituents, is the generation of bremsstrahlung. Thus, observations from balloon-borne radiation detectors, responding to X-rays, have served to complement those obtained by the ionospheric absorption technique. While this method also involves instruments which are relatively fixed in position, the time coverage of electron precipitation events has been much smaller than obtained with riometers. In addition, with the detectors generally placed well below the top of the atmosphere, this method is insensitive to the low energy (<15 keV) end of the incident electron flux due to photo-absorption of X-rays in the residual atmosphere. It does have the advantage, however, of responding *directly* to the electron precipitation, rather than through intermediate processes, and thus offers a means of examining features of time variations beyond the capabilities of riometers. Like all techniques in these studies, it generally suffers from geometrical ambiguities, making it difficult to locate where the electron precipitation occurs. As a result, absolute values of the electron influx inferred from X-ray observations are somewhat uncertain.

The detectors used in balloon experiments have ranged from Geiger counters to ionization chambers and scintillation counters. The gas-filled detectors are relatively insensitive and, by themselves, only indicate the presence of X-rays at balloon altitude. When used in combinations such as an ion chamber and a Geiger counter or two Geiger counters having cathodes of different materials, crude estimates of the X-ray energy have been obtained from their relative responses, indicating that the electron influx is mainly below 100 keV. More sensitive indications of X-ray fluxes are obtained with Na I(T1) scintillation counters, having X-ray detection efficiencies one or two orders of magnitude greater than gas-filled detectors; these counters also provide information of the X-ray spectrum at balloon altitude when used in conjunction with some form of pulse-height analysis.

For the omni-directional counters used, the photon fluxes are obtained by dividing counting rate increases due to X-rays by the detection efficiency ϵ and the geometrical

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factor G. In the case of a cylindrical detector (Geiger counter or scintillation counter) mounted with its axis of symmetry in the vertical direction, the geometrical factor G for photon fluxes isotropic over the upper hemisphere is given by

$$G = \frac{\pi}{4} al\left(1 + \frac{a}{2l}\right)$$

where a is the diameter and l is the length. In experiments to date, geometrical factors have ranged from a few square centimeters to almost 10^2 cm^2. The efficiency for X-ray detection ranges from about 0.1% for a Geiger counter to almost 100% for an Na I(Tl) scintillation counter, depending somewhat on energy. Photon fluxes deduced in this way have ranged upward from 1 photon/cm^2-sec to extreme values of greater than 10^3 photons/cm^2-sec.

X-ray observations are carried out generally at altitudes of 30–40 km, corresponding to atmospheric depths of about 5–10 gm/cm^2. The electron bremsstrahlung is produced in a layer extending down to about 80 km; in the region between the production layer and the balloon detectors, the X-ray spectrum is modified by absorption (photo-electric) and scattering (Compton) processes. Unless special geometry or shielding is employed, detectors in common use respond to X-rays originating within a horizontal distance of about 50 km from above the balloon.

The gas-filled detectors (Geiger counters and ionization chambers) show a large background due to charged particles in cosmic radiation and yield only modest increases (up to 1–2X background) in counting rate for most X-ray events. Scintillation counters, on the other hand, have a background largely due to photons generated by cosmic radiation and show much larger increases in counting rate with electron precipitation events.

A. RESULTS

1. *Correlation with ionospheric absorption of cosmic radio noise*

As would be expected, increases in counting rate of X-ray detectors at balloon altitude have been found to coincide rather closely with increases in ionospheric absorption when the balloon instruments were located within riometer antenna patterns. Since electron precipitation generally extends great distances in the E–W direction, the association of bremsstrahlung and ionospheric absorption holds up rather well even when the detectors are removed from the riometer sites, so long as there are not great differences in magnetic altitude. In any case, however, for a given detector a wide range of absorption values is obtained for a given increase in counting rate due to X-rays and vice versa. While part of this may result from geometrical factors, another important part is due to differences in the spectrum of the incident electrons. In some ways, the wide variability in the relation between X-ray fluxes and absorption resembles the results found in comparing increases in ionospheric absorption and horizontal magnetic disturbance (Barcus and Brown, 1962).

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2. *Correlations with magnetic disturbance*

The relation between X-ray fluxes and magnetic disturbance is just as complex as between absorption and magnetic variation because several types of geomagnetic field disturbances are associated with electron precipitation. In addition, there is a whole class of X-ray and absorption events without significant magnetic activity.

Starting first with positive magnetic bays which occur in the evening hours before the more active forms of auroral activity, these have been found to be associated with X-ray events (ANGER, unpublished) in addition to increases in ionospheric absorption. However, since these results come from observations late in long balloon flights during Arctic summer, there is not a vast amount of information available to document this association in detail. This is further complicated by the fact that the ionospheric current systems do not give rise to well-defined magnetic disturbances. Thus, the main result is a qualitative one showing that electron precipitation in the evening hours is associated with eastward electrojets and give fairly modest X-ray fluxes at balloon altitude as well as weak ionospheric absorption.

In the case of negative magnetic bays due to westward electrojets following auroral breakup, balloon studies (ANDERSON, 1960; BROWN, 1961; BROWN and

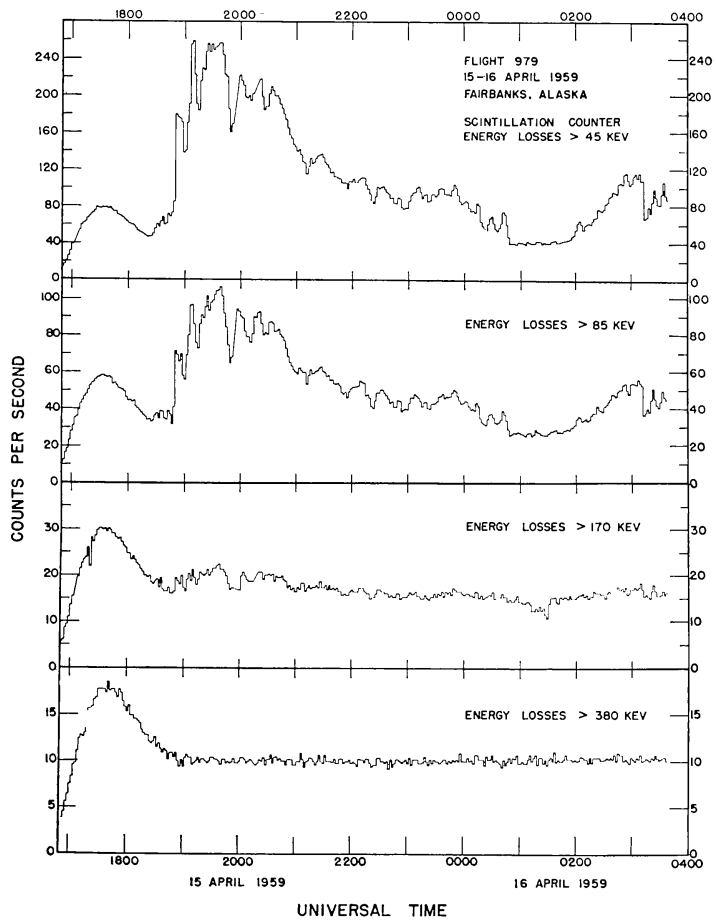

Fig. 2.1. An example of X-ray effects during an electron precipitation event. (ANDERSON, 1960.)

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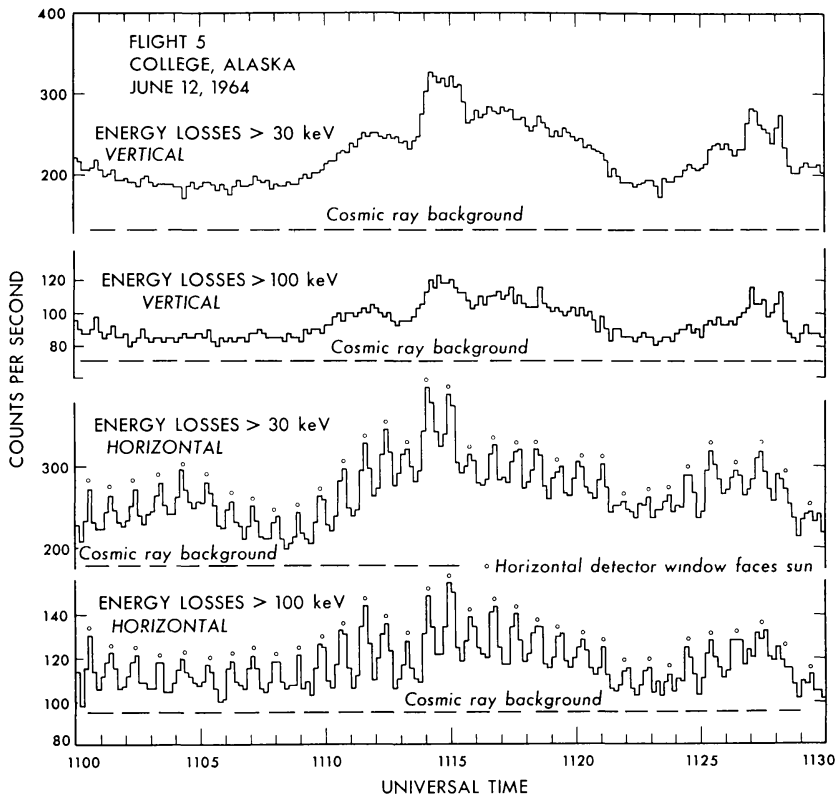

Fig. 2.2. Observations of X-rays using directionally-sensitive detectors, showing electron precipitation located to the north of the detector. (GOSLING, 1966.)

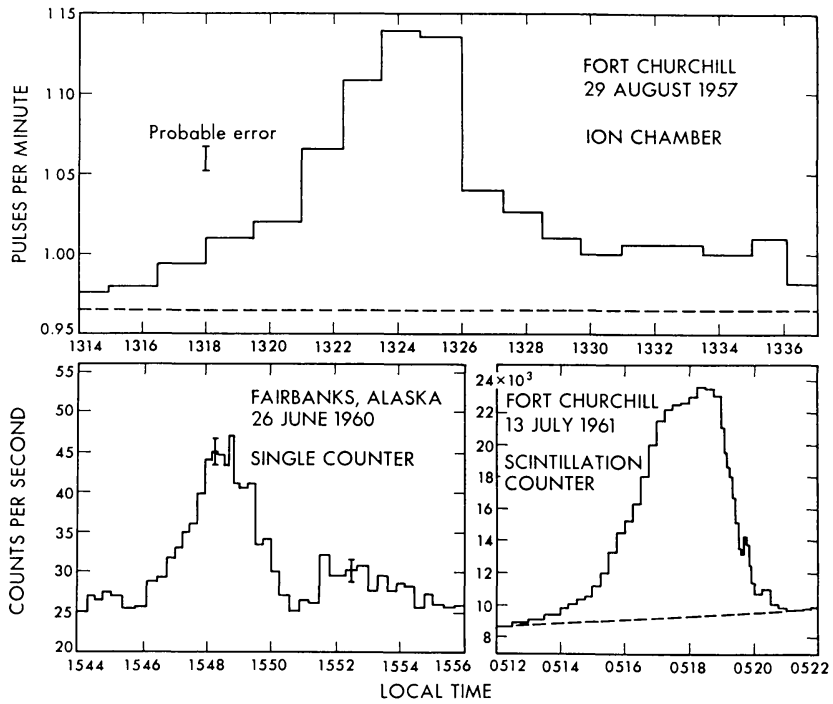

Fig. 2.3. X-ray observations at the sudden commencement of magnetic storms. (ANDERSON, 1965.)

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CAMPBELL, 1962; PFOTZER *et al.*, 1962) have shown large but variable X-ray fluxes during the magnetically disturbed periods. By way of illustrating this feature, Figure 2.1 shows a typical event at auroral latitude. It should be noted that events of this type may show slow or fast onset, depending on the character of the magnetic disturbance. Recently, CAMPBELL (1964) has reviewed magnetogram and micropulsation data for a number of X-ray events associated with bay events, showing something of the value in interpreting magnetic field effects associated with particle precipitation.

With comparisons of auroral absorption from riometer data and the position of ionospheric current systems, it was found (BARCUS and BROWN, 1962) that ionospheric absorption during bay events reached a maximum with zenith crossing of auroral electrojets, suggesting that the regions of electron precipitation coincide and move systematically with the current systems. A direct confirmation of this feature was obtained from X-ray experiments (GOSLING, 1965) using directionally-sensitive detectors. Here, two Na I(Tl) scintillators, one with maximum response in the vertical direction and the other most sensitive to X-rays from a limited range of directions close to horizontal but rotating in azimuth at one revolution per minute, were flown during a number of negative bays. During the X-ray events of this type, the directionally-sensitive detectors showed an increase in counting rate as they rotated past the directions where the ionospheric current systems were located; when the current systems moved toward the balloon detector, the ratio of the excess vertical rate to the peak horizontal rate increased and the directional response of the rotating detector essentially disappeared when the current system passed overhead. An illustration of these results is shown in Figure 2.2.

In addition to bay events, other forms of magnetic activity have been found to be associated with X-ray fluxes. Thus, balloon observations have shown X-ray fluxes coincident with the sudden commencement of magnetic storms, just as indicated earlier from ionospheric absorption studies. To date, however, only three examples have been reported in the literature: for August 29, 1957 (ANDERSON, 1958), June 27, 1960 (BROWN *et al.*, 1961) and July 13, 1961 (HOFFMAN and WINCKLER, 1963; KEPPLER *et al.*, 1963).

For this type of event, the electron influx is fairly smooth and lasts about five minutes, judging from riometer observations (BROWN *et al.*, 1960; ORTNER *et al.*, 1962). The X-ray observations generally resemble these features, as shown in Figure 2.3, although the event of August 29, 1957 showed a sudden commencement at 1910 UT and the X-ray rate reached a peak at 1925 UT, 15 minutes later. In contrast to this, the event of June 27, 1960 showed a sudden commencement beginning at 0146 UT and a peak X-ray rate shortly afterward at 0148 UT, and the event of July 13, 1961 showed a sudden commencement at 1112 UT and the X-ray peak at 1119 UT. The last X-ray event, during the PCA events of July, 1961, was heavily contaminated with gamma-rays from nuclear interactions of solar cosmic rays with atmospheric constituents.

Slow pulsations of the X-ray flux due to electron precipitation have been observed

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(ANGER *et al.*, 1963; BARCUS and ROSENBERG, 1965), similar to the case of ionospheric absorption and hydromagnetic pulsations. The number of instances where this feature has been seen is small and each has been relatively brief in duration; however, the effect is quite clear as may be seen from the event in Figure 2.4.

Most of these X-ray events have been found in the interval between dawn and noon. No clear peak-to-peak correlation has been found to exist between X-ray,

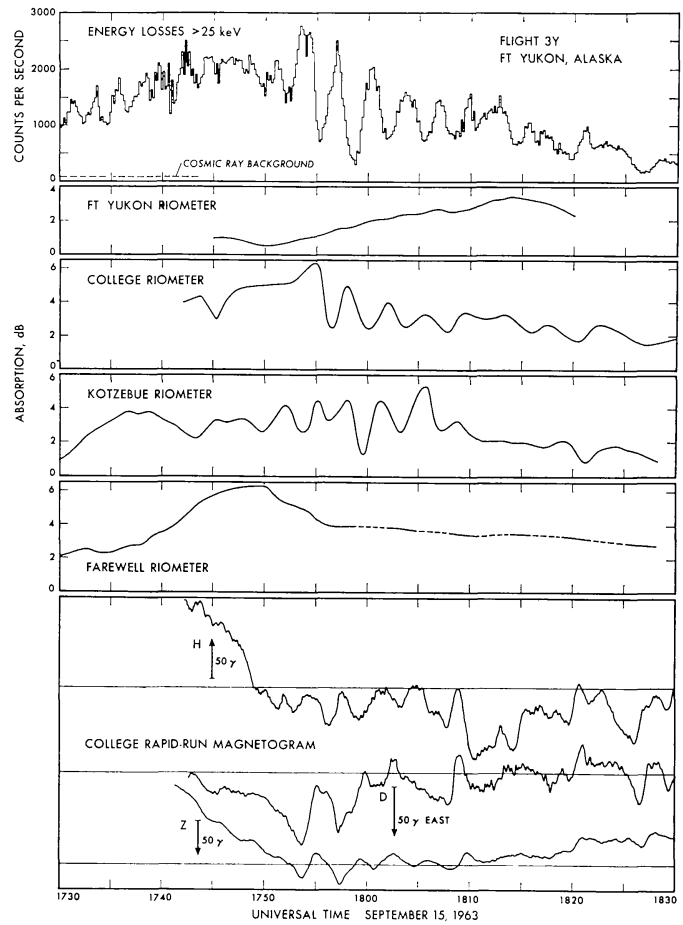

Fig. 2.4. Slow pulsations in electron precipitation, giving X-ray and ionospheric absorption pulsations. (BARCUS and ROSENBERG, 1965.)

ionospheric absorption and the corresponding magnetic pulsations. Indeed, for the conjugate event of pulsating absorption (BROWN *et al.*, 1965a) discussed earlier, balloon observations some 300 km east of one riometer site showed time displacements between the absorption and X-ray pulsations and this feature suggests a spatial structure for the pulsating electron precipitation which has a scale of a few hundred kilometers in the E–W direction. Around noon, however, instances have been found (BARCUS and ROSENBERG, 1965) where the X-ray and ionospheric absorption pulsations were in time-coincidence, to within the limits of observations, over a long distance ($\sim$1000 km) parallel to a line of latitude.

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Finally, there is a class of X-ray events, largely centered around the dawn meridian, which are characterized by little, if any, magnetic activity. These appear to be essentially the same as the slowly varying absorption events discussed by BROWN (1964); on a long time scale, their growth and decay are fairly smooth as seen on riometer records. However, on the short time scales available on X-ray records, they are frequently quite structured, showing pulsations and rapid time variations over time intervals shorter than those which the riometer can follow. KREMSER (1964) has suggested that events of this type occur at the same time as bay activity, on a scale comparable to the length of the auroral zone on the night side of the earth, but do not show local magnetic activity around dawn (local time) due to a neutral transition region in the ionospheric current systems.

3. *Association of X-rays with aurora*

This question has proved to be one of the most difficult to study for several reasons: the relatively small amount of balloon observation time during clear weather, uncertainties in balloon location during auroral displays as well as the variety of techniques (visual, all-sky camera and photometer) to observe auroral features. As a result, the amount of observational material has been rather limited, in contrast to other aspects of the electron precipitation problem, and accordingly, the questions involved have not been resolved as readily as had been hoped.

To illustrate the situation, WINCKLER *et al.* (1958) found intense X-ray fluxes under bright and active rayed forms observed visually at Minneapolis during magnetic storm conditions which brought auroral activity equatorward to $L=3.5$. On the other hand, ANDERSON (1960) found little association at Ft. Churchill ($L=8.2$) during bay events around solar maximum, small X-ray peaks being seen during the time when auroral forms were brightest and most active on all-sky camera films while the more intense X-ray peaks did not coincide with the times of maximum visual auroral activity. Additional flights (ANDERSON, 1962) from Fairbanks, Alaska ($L=5.5$) showed large fluxes above 25 keV when bright visual forms were absent from most of the sky; however, an intense X-ray burst was found to accompany the rapid motion of a bright rayed form across the zenith. Further, during a conjugate series of balloon flights, ANDERSON and DEWITT (1963) noted a space-time association between a widespread auroral glow on all-sky camera films and X-rays at balloon altitude during an intense bay event. In particular, a very close relation was noted between the auroral luminosity over the whole sky, or restricted to the area over the balloon instrument, and the X-ray intensity greater than 25 keV. This feature is shown in Figure 2.5. The correlation was such a close one as to suggest that electrons which produce X-rays at these energies during an auroral glow carry an identifiable fraction of the auroral power; however, the main input to the glow appeared to be in the form of lower-energy particles.

Another approach to the association of X-rays and auroral luminosity involved utilizing balloon-borne photometers, placing the optical system working in the visual range above the cloud cover. Here, BARCUS (1965) had found an instance of association between auroral luminosity and ionospheric absorption but little in the way of

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simultaneous X-ray flux at balloon altitude. The implication of this observation is that the electron energy spectrum was extremely steep, giving rise to ionization and luminosity at high altitudes but little in the way of X-rays that would propagate to the depth of 10 gm/cm^2.

Along this same line, ROSENBERG (1965) used a balloon-borne photometric system

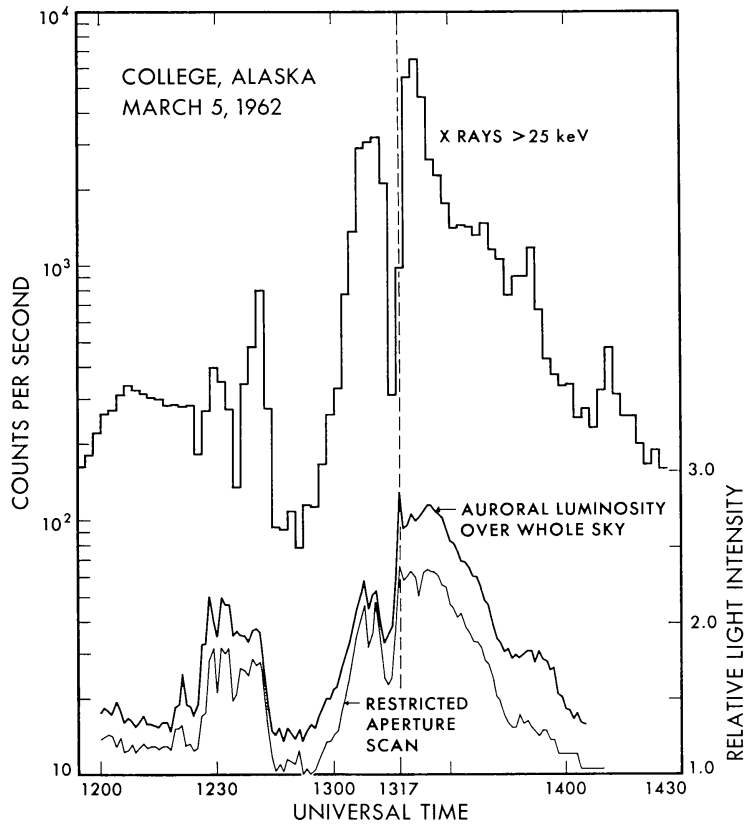

Fig. 2.5. A comparison of auroral luminosity with X-ray flux at balloon altitude. (ANDERSON and DEWITT, 1963.)

whose response peaked in the near-ultraviolet. On two active nights, the association between luminosity and X-ray fluxes ranged from instances where luminosity, X-ray intensity as well as ionospheric absorption increased simultaneously, to broad increases in each detector response without great correspondence in detail, to instances in which auroral luminosity decayed while the X-ray flux remained at moderate but steady levels. An example of this is shown in Figure 2.6.

Thus, the correlation between luminosity and X-ray intensity appears to be a loose one. The results to date would indicate that the low energy end of the electron spectrum, responsible for luminosity effects, and the high energy end, responsible for bremsstrahlung, can be relatively independent on occasions yet coupled on others. Ionospheric absorption results from electron precipitation at either end of the spectrum; whether the absorption is correlated with luminosity or X-ray fluxes depends on whether the energy spectrum is steep or relatively flat.

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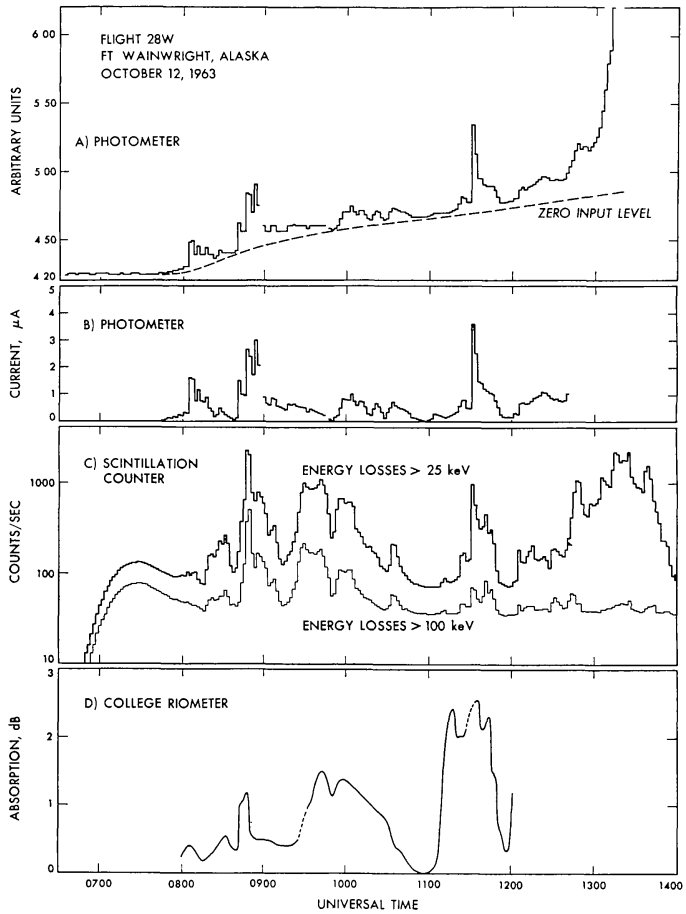

Fig. 2.6. Luminosity, X-ray and ionospheric absorption measured during an auroral event. ROSENBERG, 1965.)

4. *Spatial distribution*

To date, the principal studies of the extent of electron precipitation have been directed at the latitude distribution. Thus, WINCKLER *et al.* (1962) obtained two measurements of the latitude profile during magnetic storms while BROWN and BARCUS (1963) and BARCUS and ROSENBERG (1966) examined features for small separations at auroral latitudes.

The results of WINCKLER *et al.* (1962), during the gradual commencement storm starting September 24, 1961 and the sudden commencement storm on September 30, 1961, spanned a range of magnetic latitude from Flin Flon, Manitoba (64.5°) to Waterloo, Iowa (52.8°), at nearly the same longitude. These observations, covering about half a day's time in each storm, showed that latitude profiles during the peak intensity of these balloon flights were quite different, the gradual commencement storm showing more precipitation at auroral latitudes than the sudden commencement storm, as shown in Figure 2.7.

For smaller separations in the auroral zone, observations have been obtained during bay and storm conditions as well as events in the morning hours not accompanied by magnetic activity. Between Ft. Yukon (66.6°) and College (64.6°), Alaska,

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balloon flights have shown both broad and narrow electron precipitation events. Thus, the results of BARCUS and ROSENBERG (1966) show instances where the electron precipitation extended from Ft. Yukon to College as well as others having extent small compared to the separation (about 200 km) between the two balloon instruments.

Other observations have been obtained in which balloon instruments were separated in longitude; generally, these involve small distances (about 250 km) in the

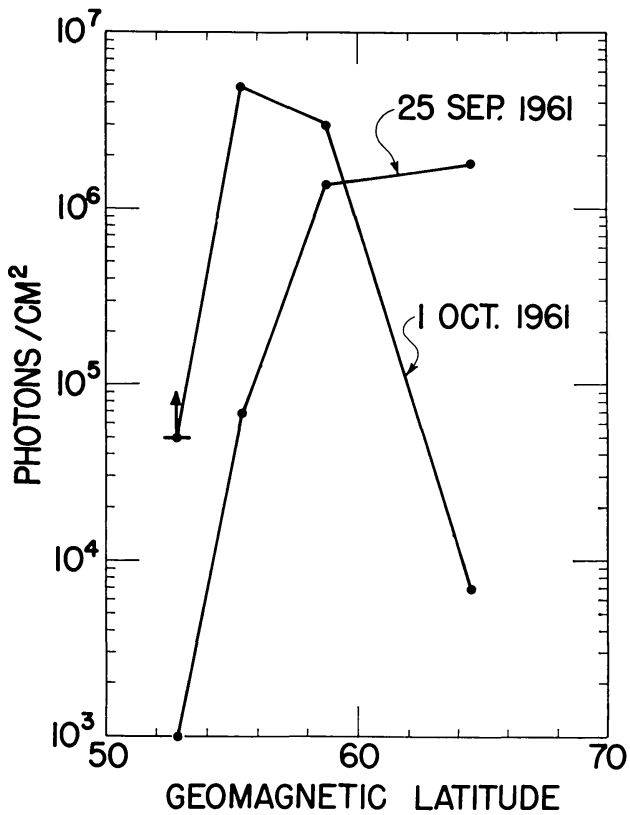

Fig. 2.7. Latitude variation of time-integrated photon flux above 20 keV during gradual commencement (September 25, 1961) and sudden commencement (October 1, 1961) magnetic storms. (WINCKLER *et al.*, 1962.)

E–W direction (BARCUS and ROSENBERG, 1966). For similar detectors, the correspondence of the X-ray records is quite good and indicates a larger E–W extent to the electron precipitation than in the N–S direction, as indicated earlier.

By coincidence, similar detectors have been aloft simultaneously at comparable latitudes but separated by almost 180° in longitude. While the number of instances has been relatively few, comparison of the observations has proved interesting. Thus, KREMSER (1964), by comparing Geiger counter recordings over College, Alaska and Kiruna, Sweden during magnetic storm conditions, has shown instances where intense precipitation was occurring around the dawn meridian while little, if any, was evident at the dusk meridian. In this study, it was emphasized that electron precipitation could occur around dawn, without appreciably magnetic disturbance, while magnetic

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records at other longitudes would show disturbance due to electrojet current systems. By way of explanation, reference was made to the current system deduced by SILSBEE and VESTINE (1942) for an average polar magnetic substorm; this shows a neutral transition region around dawn, with nighttime and daytime electrojets on either side. Similar conclusions were reached by BARCUS and BROWN (1963) from simultaneous X-ray observations with small separations; in this instance there was a significant disparity between local and planetary *K* indices at the same Universal Time, suggesting that pronounced magnetic activity was occurring at other longitudes than where the balloon flights were conducted.

Conjugate aspects of electron precipitation at auroral latitude have been examined using balloon-borne instruments as well as riometers. Because of logistic factors and other problems, however, it has not been possible to have X-ray detectors in positions of close conjugacy; rather, the work to date (BROWN *et al.*, 1963, 1965) has dealt with features in conjugate *regions*.

For intense disturbances, covering a broad range in latitude and a wide range of longitude, considerable similarity and simultaneity in electron precipitation was evident in the two hemispheres. An example of this is shown in Figure 2.8, summarizing

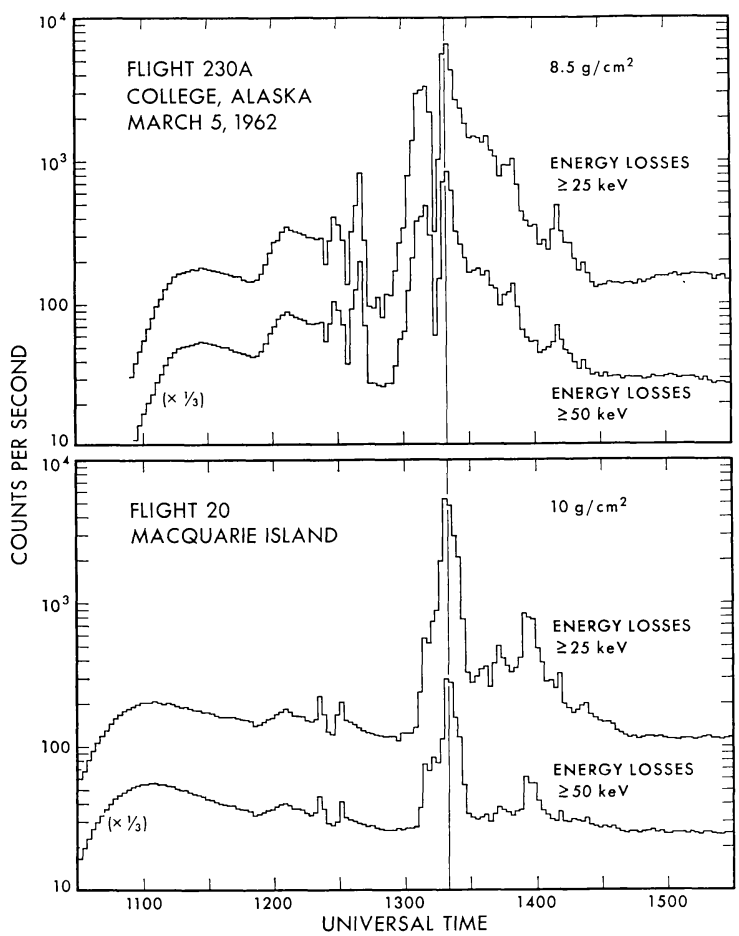

Fig. 2.8. X-ray observations in conjugate regions during an intense electron precipitation event. (BROWN *et al.*, 1963.)

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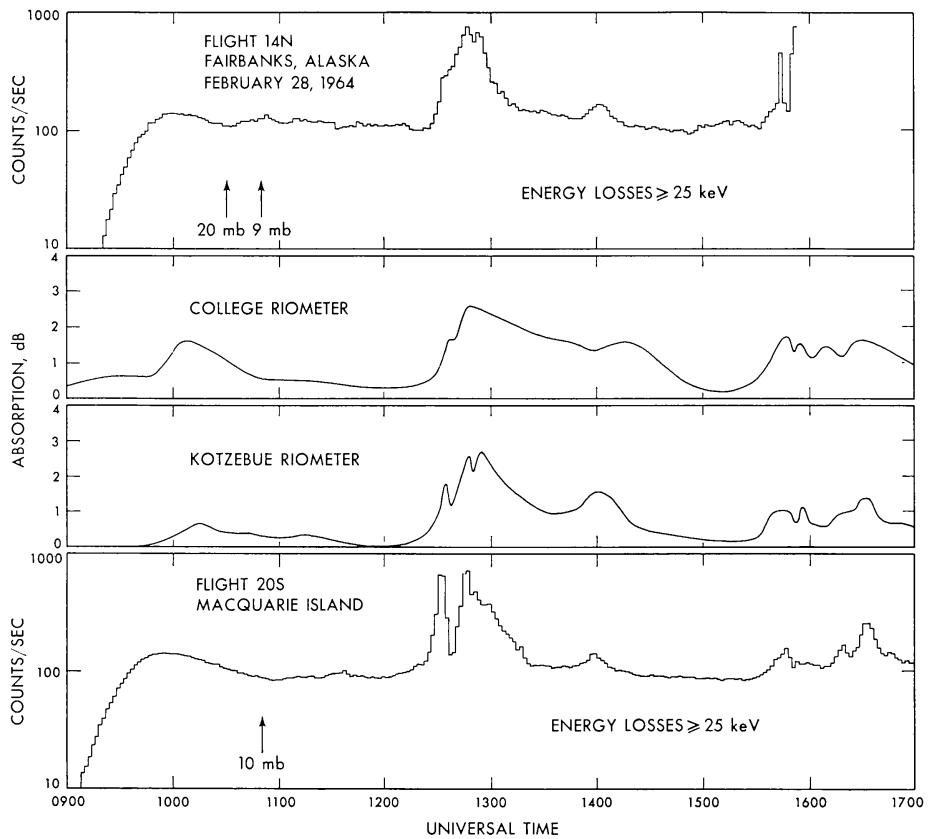

Fig. 2.9. X-ray and riometer observations in conjugate regions during a modest electron precipitation event. (BROWN *et al.*, 1965.)

observations (BROWN *et al.*, 1963) between College, Alaska and Macquarie Island, Australia, during a 850 γ bay event. In this case, the detectors were separated in magnetic longitude by 14 degrees and magnetic latitude by about 3 degrees. Even with this disparity in position, the X-ray fluxes at the height of the event were essentially equal and peaked at the same time. This argues for a symmetrical precipitation process, particles moving away from the equatorial regions in essentially equal numbers.

A second series of conjugate flights (BROWN *et al.*, 1965) gave data over a wider range of geophysical disturbance ($K_p = 0_+$ to 6_0) than the event in the first series. In addition, with a greater quantity of data to work with, it was possible to make more effective use of riometer records at Kotzebue, close to the conjugate point for Macquarie Island. As an illustration of the results obtained, Figure 2.9 shows a summary of balloon and riometer observations for February 28, 1964. This shows activity in both hemispheres, but closer correspondence is evident between the records of Macquarie Island balloon and the Kotzebue riometer.

5. *Temporal Structure*

In addition to long-period pulsations in ionospheric absorption and X-ray fluxes which accompany similar pulsations in the geomagnetic field, several other forms of pulsating electron precipitation have been observed. These are generally of shorter

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period and not clearly associated with any particular form of magnetic disturbance. For example, EVANS (1963) reported an intense X-ray event in the 80–100 second period range lasting about a half an hour during a minor (130 γ) bay event. The ionospheric absorption was rather weak (1.2 dB) at this time, suggesting that the intense electron influx was quite localized.

Another type of event, somewhat shorter in period, was observed by BARCUS and CHRISTENSEN (1965). Here, the X-ray flux varied in a manner close to sinusoidal with a period of approximately 75 seconds, as shown by the power spectrum of the intensity variations in Figure 2.10. Like the long-period pulsations, the temporal

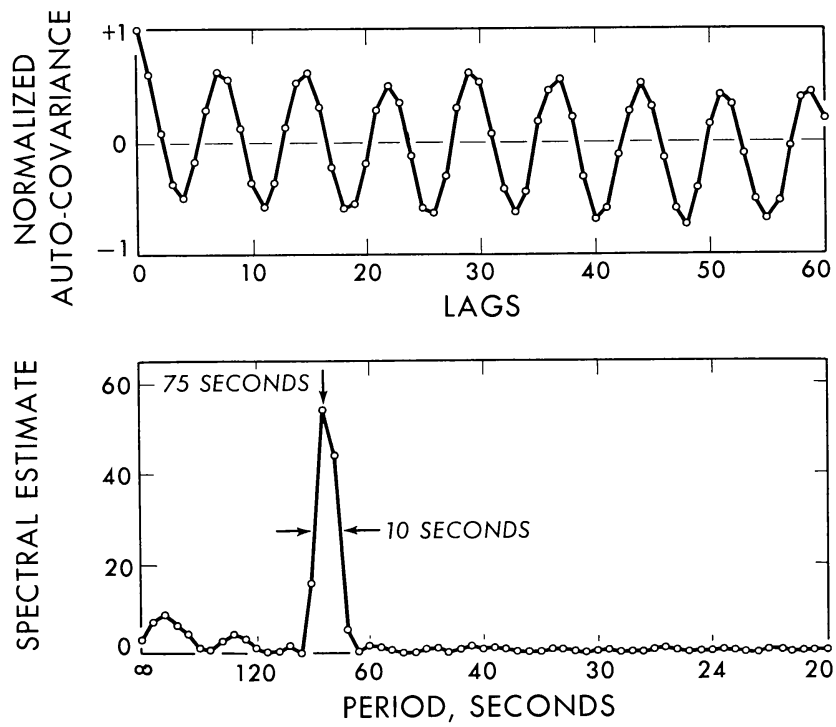

Fig. 2.10. Statistical features of a pulsating electron precipitation event. (BARCUS and CHRISTENSEN, 1965.)

aspects of this event strongly indicate a modulation of the electron precipitation already in progress. Since the periods involved are close to those for hydromagnetic waves in their various modes at auroral latitudes, the modulation would seem to be related to hydromagnetic processes taking place in the electron source region. No information is available concerning the spatial structure during this event.

It is interesting to note that the modulation of ionospheric absorption or X-ray fluxes from electrons precipitating into the atmosphere is similar to the recently reported modulation of VLF emissions due to particles much farther up along field lines. Here, CARSON *et al.* (1965) found that well-known emissions (hiss and rising chorus) show long period pulsations in the same time range, the normal VLF signals being periodically emitted at increasingly higher frequencies. These long period pulsations increase in period with increasing latitude and are found to be simultaneous

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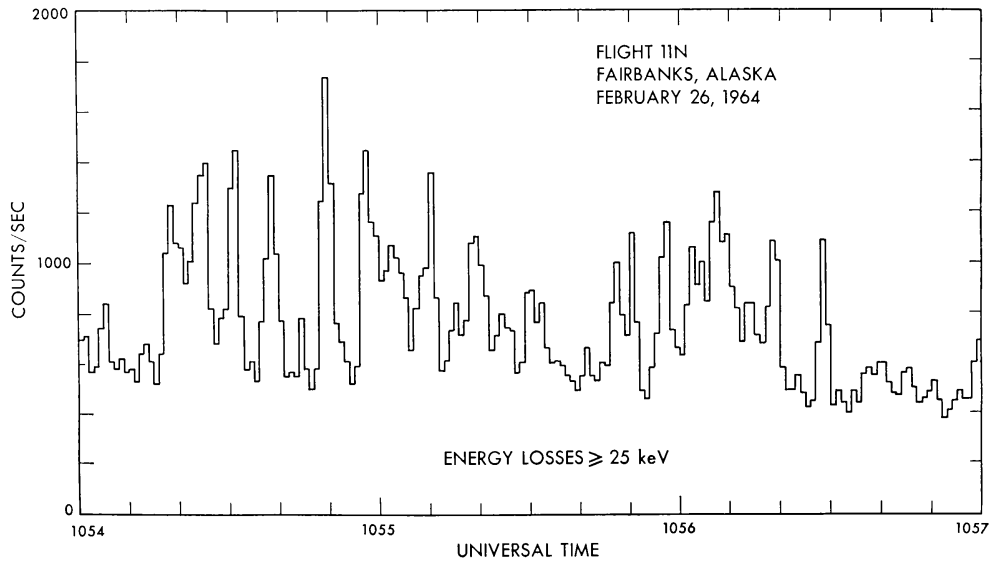

Fig. 2.11. Irregular pulsations in X-ray intensity. (BROWN *et al.*, 1965b.)

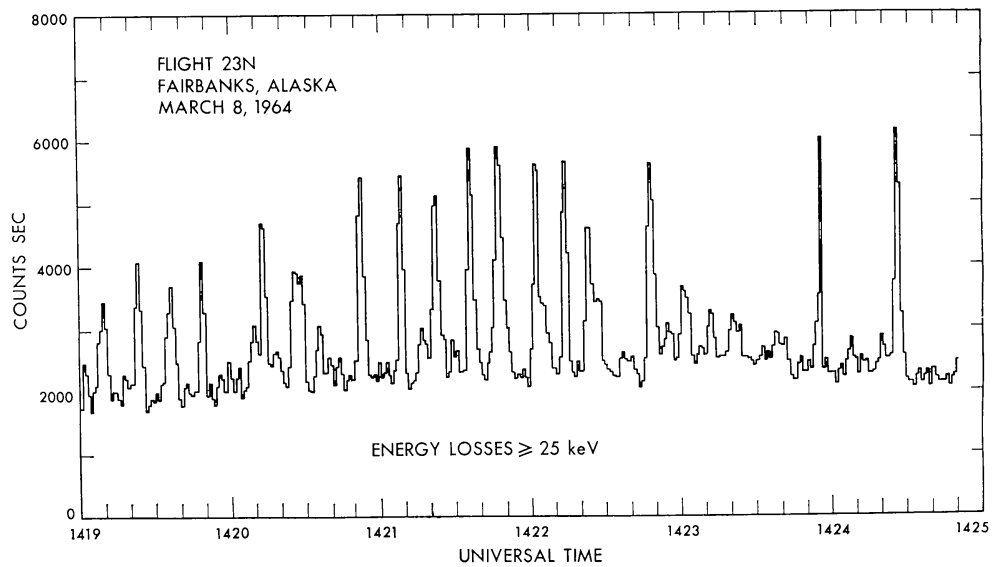

Fig. 2.12. Semi-regular pulsations in X-ray intensity. (BROWN *et al.*, 1965b.)

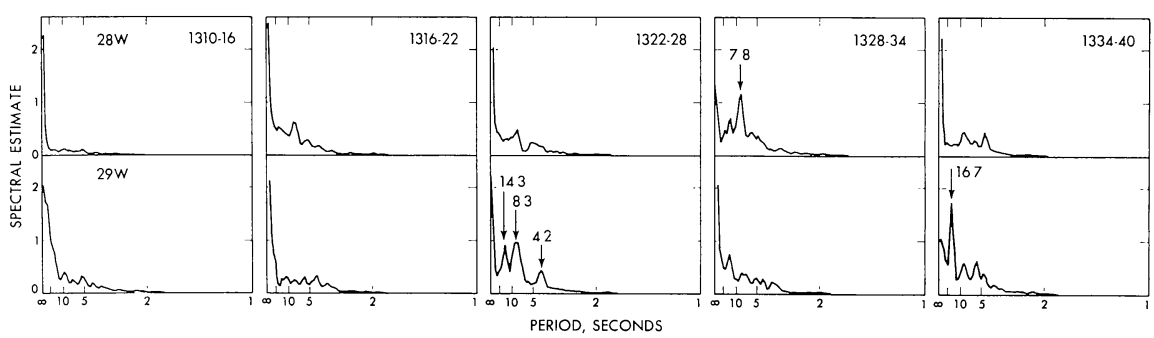

Fig. 2.13. Consecutive power-spectra for simultaneous X-ray observations from two balloon-borne scintillation counters. (BARCUS *et al.*, 1966.)

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in conjugate regions. Thus, the implication of these observations is that hydromagnetic waves on field lines are capable of modifying the parameters of the precipitation process for energetic electrons as well as those of the VLF process. In both cases, the processes must be in progress for the hydromagnetic waves to be effective and, further, hydromagnetic waves alone are unable to give rise to the processes (precipitation or VLF emission).

At an even shorter time scale, the most common form of X-ray pulsation is found, ranging from 5 to 15 seconds between consecutive X-ray peaks (ANGER *et al.*, 1963; BARCUS *et al.*, 1965). These pulsation events occur predominantly around the dawn meridian and generally represent a significant fraction of the particle influx at these times. Two examples of pulsations in this time range are shown in Figures 2.11 and 2.12; the irregular type in the first figure is more frequently encountered that the regular appearing type in the second figure. While the change in X-ray flux at 10 gm/cm^2 can reach values $\sim 10^3$ photons/cm^2-sec, more typical values are 10^1–10^2 photons/cm^2-sec above 25 keV.

X-ray pulsations of this nature are often found during magnetic bays and, as indicated by CAMPBELL (1961), are accompanied by micropulsations (1–10 γ) of the geomagnetic field with periods in the same range. Because of differences in effective apertures of X-ray detectors at depths around 10 gm/cm^2 and micropulsation equipment, it has not proved possible to find peak-to-peak correlations between the two effects. CAMPBELL (1964) has shown that only small (1%) changes in electron density are required to produce variations of ionospheric conductivity necessary for electrojet fluctuations; these changes presumably arise from temporal and spatial variations in the electron precipitation.

Estimates of the horizontal extent of electron precipitation pulsations have been obtained from simultaneous balloon flights (BROWN *et al.*, 1965) carrying X-ray detectors separated by distances of the order of 100 km. Thus, for example, from one set of observations with balloons spaced by about 100 km in the N–S direction, it was found that the cross-correlation function for the X-ray flux at zero time lag was quite high (~ 0.7) while another set of observations with balloons spaced by about 150 km in the E–W direction showed a low cross-correlation (~ 0.2). As a result it was concluded that pulsating electron precipitation is coherent over distances close to 100 km; beyond that the coherence breaks down.

From analyses of power spectra, it has become evident that the temporal character of these events is non-stationary in time. Thus, as pulsations develop and the X-ray intensity becomes more structured, the power spectra develop peaks in the range between 2 and 20 seconds. An illustration (BARCUS *et al.*, 1966) of this feature is given in Figure 2.13, showing consecutive power spectra for X-ray intensity variations over a half hour interval. Those peaks for which periods are indicated are statistically significant at the 10% and 90% confidence limits.

Extending this type of analysis to a 30-minute section of data from two pulsating events (BARCUS *et al.*, 1966) brought out a significant spectral peak at about 8 seconds for both cases. While this result indicates a tendency for bursts to recur with this

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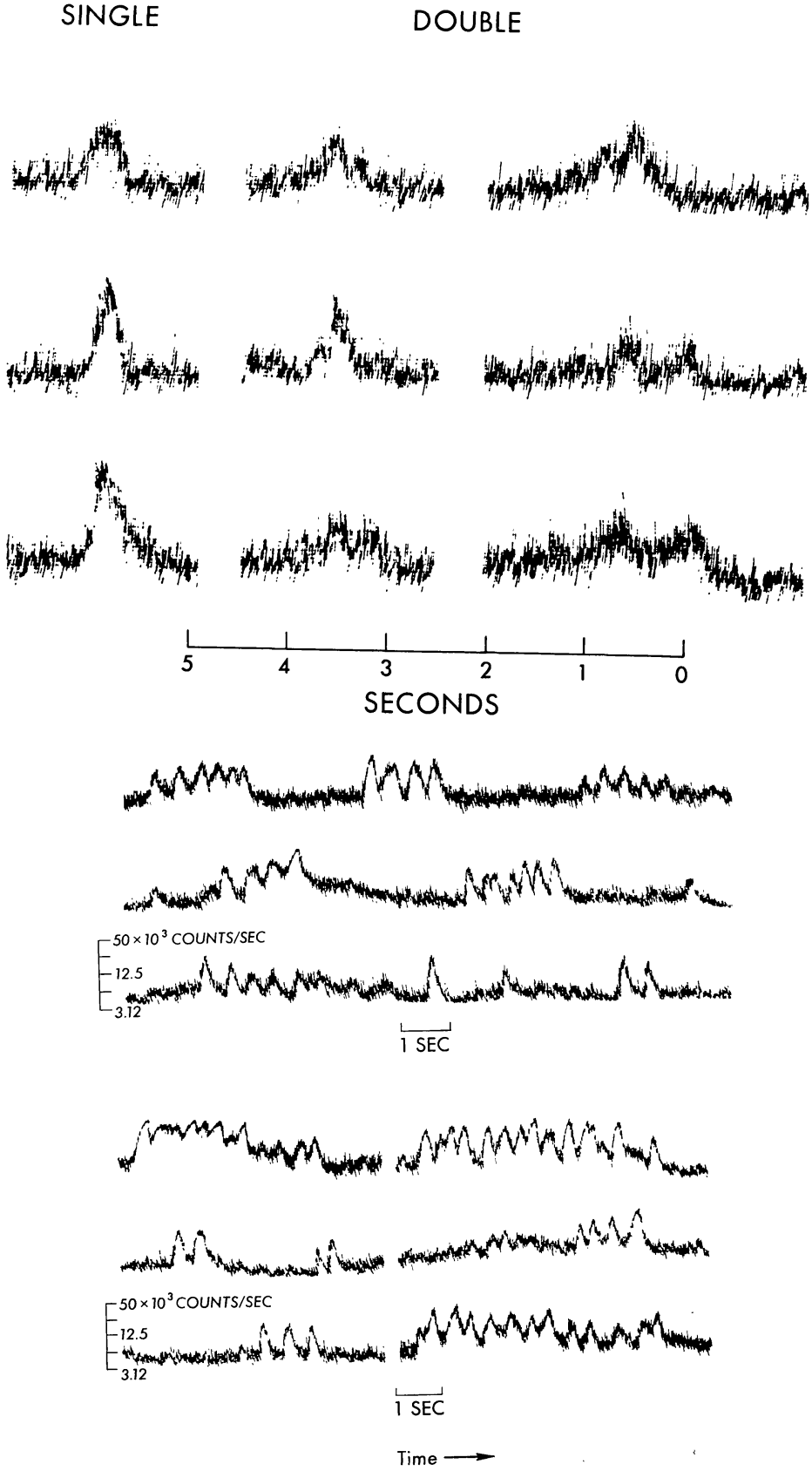

Fig. 2.14. Examples of microbursts recorded by a scintillation counter and a fast-response counting-rate meter. (ANDERSON and MILTON, 1964.)

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spacing, it is by no means a unique value; other pulsating events have been observed for which the spacing is smaller or larger and WINCKLER *et al.* (1962) have discussed an event showing large fluctuations where spectral analysis of the data showed the statistical character of random noise.

While the time scales of the preceding types of X-ray pulsations are far too long to be directly associated with the dynamical motions of electrons trapped in the geomagnetic field, pulsations have been reported close to the electron bounce period. Thus, WINCKLER *et al.* (1962), subjecting an hour of high intensity X-ray data to power spectrum analysis, found spectral peaks at periods of 0.8 and 1.6 seconds, respectively. The peak at 0.8 seconds corresponds to the bounce period of 60 keV electrons on the line of force ($L=3.5$) through Minneapolis; these electrons would produce X-rays capable of reaching balloon altitude. The other peak at 1.6 seconds corresponds to the bounce period of lower energy electrons whose bremsstrahlung would be below the threshold of balloon detectors. Thus, the interpretation of the spectral peak at 1.6 seconds requires another factor than the mirroring motion associated with the peak at 0.8 seconds.

At this time-scale, another striking feature of electron precipitation is found in the brief, intense X-ray peaks termed "microbursts" by ANDERSON and MILTON (1964). These have a fairly characteristic duration in time, approximately 0.2 seconds at half-intensity, and are found to occur individually or in groups. An illustration of single and double microbursts, recorded by a large area scintillation detector which fed a fast-response logarithmic counting rate meter (ANDERSON and MILTON, 1964), is given in Figure 2.14; in addition, multiple microbursts have been recorded by the same detector system.

Features of the spatial distribution of electron precipitation during microbursts have been obtained from simultaneous balloon flights in the auroral zone. These observations have shown that microburst precipitation is quite localized. For example, during a period of microburst activity when two X-ray detectors were aloft, separated by about 150 km in the magnetic E–W direction, microbursts in time-coincidence were observed (BROWN *et al.*, 1965). While the examples in Figure 2.15

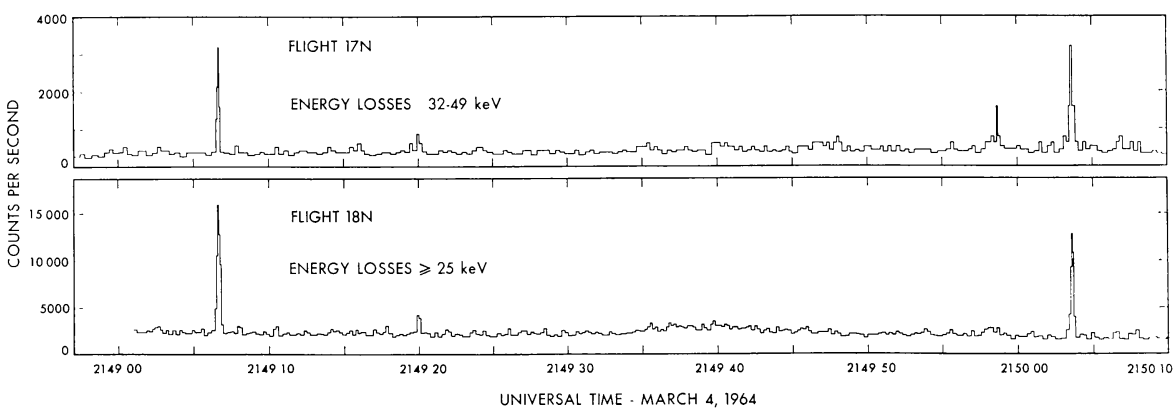

Fig. 2.15. An example of intense microbursts in time coincidence, recorded by balloon instruments separated by approximately 150 km. (BROWN *et al.*, 1965b.)

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illustrate this feature, it was found that only about one-third of all the microbursts were in coincidence; the remaining fraction was recorded on one balloon instrument or the other. Thus, the scale-size of microburst precipitation appears quite small, extending over distances of the order of a few hundred kilometers.

Confirmation of this result was obtained by TREFALL *et al.* (1965), flying X-ray detectors at an E–W separation of about 300 km. Here, it was found that while microbursts were observed on both balloons during a period of disturbance, the number of time-coincidences of microbursts was no greater than the number of accidental time coincidences expected on the basis of the microburst rates shown by each balloon detector.

A different approach to examining the spatial structure of microburst precipitation was taken by PARKS *et al.* (1965), employing three collimated X-ray detectors flown at extreme altitude (~ 3 gm/cm^2) in a single balloon payload. In this altitude range, scattering does not seriously influence the observations and the detectors each viewed a region about 30 km across at the 100 km level, separated by 120° in azimuth and at 30° from the zenith. These observations indicated that the pattern of electron precipitation during microbursts was complex, with no unique source size or systematic motions in space.

Another aspect of the temporal features of electron precipitation concerns the similarity and simultaneity of effects in the northern and southern hemispheres, particularly for fast time variations where it might be possible to observe time shifts between X-ray peaks at the two ends of lines of force. While the results obtained to date are somewhat limited, they seem to bear out the idea that electron precipitation is symmetrical, at least at suroral latitudes. Thus, an example of slow pulsations (BROWN *et al.*, 1965) of electron precipitation and ionospheric absorption has been found in time coincidence in conjugate regions. In this same period range, CHIVERS and HARGREAVES (1964) have reported cases of time shifts of about one minute between hemispheres for conjugate stations at $L=7$. On a faster scale, although detailed comparison has not proved possible yet, indications (BROWN *et al.*, 1965) are that pulsating electron precipitation activity in the 5–15 second range occurs at the same time in the two hemispheres.

6. *X-ray and electron energy spectra*

Early measurements (WINCKLER, 1958; ANDERSON, 1958) indicated that the X-ray fluxes at balloon altitude were in the range around 50 keV, the energy estimates being obtained by comparing the responses of two gas-filled detectors as well as the absorption of photons in the atmosphere. With this result, attempts were made to find features of the electrons at the source region by using thick-target bremsstrahlung theory and the absorption (photo-electric) as well as scattering (Compton) of photons between the production layer and the balloon level. Taking trial electron spectra and then calculating the transmission of photons in each energy interval, the relative responses of ionization chambers and Geiger counters at balloon altitude were evaluated for comparison with experimental data.

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By way of illustration, semi-empirical thick-target bremsstrahlung theory (EVANS, 1955) indicates that the number of photons radiated in the range (E_γ, dE_γ) by a single electron of energy E is given by

$$\frac{\mathrm{d}N}{\mathrm{d}E_\gamma} = KZ\frac{(E - E_\gamma)}{E_\gamma}$$

where $K = (1.4 \pm 0.4) \times 10^{-3}$ (MeV)$^{-1}$ and Z is the atomic number of the absorber (air). Taking this expression, weighting it according to the number of electrons in the primary (trial) spectrum for the range (E, dE) and assuming that the photons start from a broad region at the source level, the responses of different detectors may be calculated. For an omni-directional detector (such as a spherical ionization chamber) of cross sectional area S, the response to photons of energy E_γ produced in an area dA is given by

$$PI_0 \frac{S}{4\pi R^2} \exp\{-\mu(E_\gamma)x/\cos\theta\}\,\mathrm{d}A$$

where I_0 is the source strength in photons/cm^2-sec, R is the distance from the detector to the source area dA, θ is the angle between the vertical and R, x is the number of gm/cm^2 of air in the vertical direction between the detector and the source level and $\mu(E_\gamma)$ is the appropriate absorption coefficient in cm^2/gm. The factor P represents the response of the detector to photons of energy E_γ; for an omni-directional Geiger counter, P would be the efficiency (ϵ) while for an ionization chamber, it would be khv, where k is the number of pulses per unit energy dissipated in the chamber.

As a first approximation, the absorption coefficient for use in calculating the response of an ionization chamber is the sum of the photo-electric and Compton coefficients; this gives a measure of the energy absorption of X-rays in the atmosphere. For Geiger counters, which respond to individual photons rather than energy losses, the photo-electric coefficient is used. The total responses for each instrument is found by integrating over the photon spectrum at the source.

The photo-electric absorption and Compton scattering coefficients for photons in air are given in Table III, covering the energy range of interest to the electron

TABLE III

Photoelectric and Compton scattering coefficients in air

Photon Energy (keV)	Photoelectric Absorption Coefficient (cm^2/g)	Compton Scattering Coefficient (cm^2/g)
10	4.2	0.190
15	1.2	0.185
20	0.50	0.175
30	0.13	0.165
40	0.050	0.160
50	0.025	0.155
60	0.013	0.150
80	0.005	0.135
100	0.0025	0.125
150	—	0.105
200	—	0.093

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precipitation problem. The strong photo-electric absorption in air at 20 keV indicates that the bremsstrahlung spectrum below this energy in the source region will not reach balloon altitudes.

Refinements in the calculations outlined above include the energy scattered between the source and the detector levels but recorded by the detectors. Since the important portion of the spectrum (20–200 keV or so) lies well below the electron rest energy, the change in photon energy by scattering is only a relatively small amount (HEITLER, 1954).

Working in this way, parameters of the assumed electron spectrum have been determined to give the best agreement with experimental ratios. In a summary of events observed at Minneapolis, MAY (1961) gives a number of cases where an inverse power law works well, the exponent γ falling between 3 and 4.

Under most circumstances, this approach to the electron precipitation problem has its limitations, not much more than order of magnitude estimates of the electron influx being obtained without a detailed knowledge of the location and extent of the precipitation region relative to the balloon detector and the angular distribution of the incident particles.

With the introduction of Na I(Tl) scintillation counters and integral pulse-height discriminators, the first measurements of X-ray spectra at balloon altitude became available and prompted more detailed calculations aimed at evaluating features of the electron influx. Thus, Anderson and Enemark (1960) calculated the number of photons above the discrimination level E_a produced by an electron of initial energy E traversing its range in air:

$$N(E_a; E) = \frac{1}{2000\, L_R}\left\{E\left(\ln\frac{E}{E_a} - 1\right) + E_a\right\}$$

where L_R is the radiation length in air, using the relativistic bremsstrahlung cross section

$$\frac{d\sigma(h\nu)}{d(h\nu)} = \frac{A}{h\nu}$$

and the approximate range-energy relationship for electrons

$$R = E/2000$$

where E is in keV and R is in gm/cm^2.

For higher discrimination levels, identical expressions apply, except for a change in subscript. Thus, for N electrons of energy E, the number of photons produced in the energy interval E_a to E_{a+1} is given by

$$N(E_a; E_{a+1}) = \frac{N(E)}{2000\, L_R}\left\{E \ln\frac{E_{a+1}}{E_a} - (E_{a+1} - E_a)\right\}$$

By taking trial electron spectra of the forms

$$\frac{dN}{dE} = AE^{-\gamma} \qquad \text{and} \qquad \frac{dN}{dE} = Be^{-E/E_0}$$

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photon spectra at the source region were obtained; assuming the source to be broad and treating the propagation of photons as indicated earlier, X-ray spectra were calculated for comparison with experimental data at balloon altitude.

This approach to the spectrum problem may be improved upon by introducing better approximations to the bremsstrahlung cross section than the relativistic case as well as the range-energy relation summarized by SPENCER (1959). A recent calculation (REES, 1964) has employed the non-relativistic bremsstrahlung theory of Sommerfeld, as developed by KIRKPATRICK and WIEDMAN (1945). This gives fewer low-energy photons than the simpler formulations of the problem. A more detailed treatment of the diffusion of X-rays through the atmosphere would represent an improvement in the theoretical analysis of the problem. To date, this has not been realized, largely because inadequate knowledge of the extent and location of the precipitation regions does not warrant attempting to solve the X-ray transport equations.

To illustrate the fluxes and spectra of X-rays found during electron precipitation events, several results will be cited. Thus, ANDERSON (1960) encountered photon fluxes above 40 keV ranging from 10^1 to 10^2 cm^{-1}-sec^{-2} during events of modest ($7X$ background) intensity at Ft. Churchill, Canada ($L=8$). These values were inferred from observations with a cylindrical Na I(Tl) detector, weighting the sensitive area isotropically with respect to solid angle. By way of contrast to these observations at auroral latitude, more than 160 hours of observation at comparable altitudes over the north magnetic pole yielded no detectable X-ray fluxes with similar detectors.

Further observations were reported by ANDERSON and ENEMARK (1960b) from balloon flights over Fairbanks, Alaska ($L=5.5$); here, using four-channel integral pulse height discriminators with omni-directional detectors, X-ray observations during other low intensity events were examined for the differential electron spectra at the top of the atmosphere. Using a power-law representation, it was found that steep electron spectra were required to fit X-ray data from 25 to 300 keV, the power-law exponent falling in the range between 5.0 and 5.5. Using an exponential spectrum, these data were fitted between 25 and 100 keV with an *e*-folding energy of 25 keV. For such a low-intensity event, the integral electron flux above 25 keV was calculated to be 4×10^6 electrons/cm^2-sec. For comparable conditions, more than 120 hours of observation with gas-filled detectors yielded little in the way of observations of X-rays, primarily because of the lower intrinsic efficiencies of these detectors.

BHAVSAR (1961), making scintillation counter observations of X-rays at sub-auroral latitudes during a period of intense geomagnetic disturbances, examined the X-ray spectrum between 22 and 263 keV with a cycling pulse attenuator which fed a fixed pulse-height discriminator. For an intense auroral peak in the X-ray data during a PCA event, the low energy portion of the X-ray spectrum gave an integral electron spectrum with exponent $\gamma\cong7$ while the average spectrum gave $\gamma\cong5$. The peak electron flux during this event was evaluated as 10^9 cm^{-2}-sec^{-1} greater than 22 keV, giving an indication of the extreme values that can be reached during electron precipitation events.

In a recent work, BARCUS and ROSENBERG (1965) examined the spectral features of

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X-rays recorded by uncollimated Na I(Tl) crystals, using both three-channel integral and eight-channel differential pulse height analyzers. More than one thousand spectra were evaluated with each type of equipment, the data being averaged over 120 second intervals.

The differential pulse height data showed that the auroral X-ray intensity at depths of 8–10 gm/cm^2 increases from below 20 keV to a maximum around 30–50 keV and then show a monotonic decrease to higher energies, as shown in Figure 2.16. The peak in the spectrum is due to strong photo-electric absorption below 30 keV; beyond this, the X-ray spectra represent an indication of the behavior of the production spectrum at the top of the atmosphere as well as the incident electron energy spectrum at slightly higher energies.

Limiting consideration to X-rays beyond the peak in the spectrum and analyzing the intensity ratios in terms of exponential spectra, these observations were used to

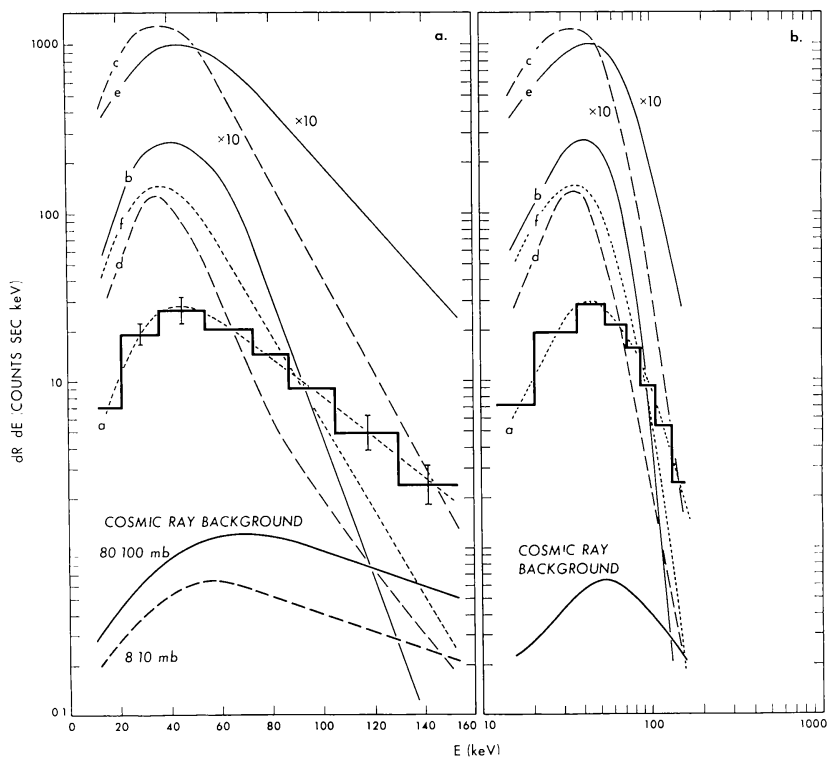

Fig. 2.16. Examples of X-ray spectra at balloon altitude ($\sim$ 8 gm/cm^2) during electron precipitation events. (Barcus and Rosenberg, 1966.)

obtain a measure of the relative frequency of occurrence for *e*-folding energies of the spectra. For two active periods, the results are shown in Figure 2.17; essentially the same distribution was obtained with each type of instrument, showing a strong peak around $E_0 \sim 20$–30 keV with extreme values of 10 to 50 keV.

For the range of atmospheric depths available in the experiment, the presence of softer spectra ($E_0 \leqslant 10$ keV) was obscured somewhat by atmospheric absorption; only for the most intense events associated with strong activity were steep spectra observed.

By taking these data and sorting out the different temporal features of electron

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precipitation, it proved possible to show something of the variation in spectral behavior from class to class. Thus, the sporadic pre-breakup X-ray fluxes appeared fairly hard ($E_0 \sim 25$–40 keV) and were followed by softer ($E_0 \sim 10$–30 keV) X-ray in the post-breakup phase associated with ionospheric current systems. From dawn to noon, when X-rays are often observed in the absence of significant magnetic activity, the spectra were again somewhat harder. In this same interval, long-period pulsations were observed but did not differ appreciably in their spectra from that of the slowly varying enhanced background on which they were superimposed. This feature lends support to the idea that such pulsations result from a modulation of the precipitated electron flux rather than a different process requiring some other form of energization.

For the fast pulsations which occur around the dawn meridian, the *e*-folding energies were lower ($E_0 \sim 15$ keV) than the slow background ($E_0 \sim 25$–30 keV). This

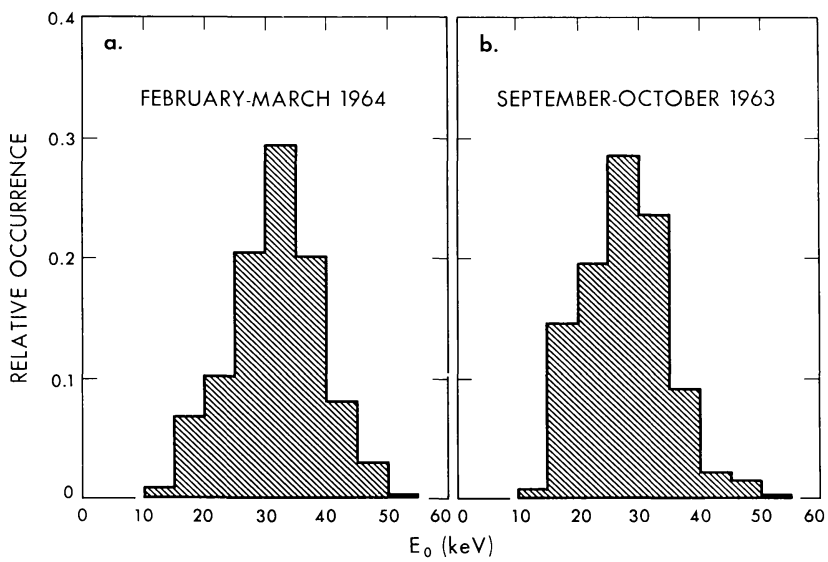

Fig. 2.17. Occurrence distributions for e-folding energies of auroral X-ray spectra at balloon altitudes. (BARCUS and ROSENBERG, 1966.)

suggests that two spectral types of precipitation take place simultaneously, the softer pulsating precipitation being localized within the harder, more extensive precipitation. In contract to this, microbursts, which are known to be small scale events, appear to have hard ($E_0 \sim 30$ keV) spectra like the background. All these spectral features are summarized in Figure 2.18 showing their diurnal pattern in the auroral zone and the relation to DS currents.

While the results cited above give an indication of the relative variability of auroral zone X-ray spectra, they are only semi-quantitative as far as the primary electron spectra are concerned. By means of flights at extreme altitudes (~ 3 gm/cm^2) efforts (HUDSON *et al.*, 1965) have been made to obtain more precise results. Here, measurements were made at atmospheric depths less than one Compton interaction length. In addition, by using thin Na I(Tl) crystals, high energy photons did not contaminate

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the X-ray spectrum by Compton scattering in the detector. By collimating the detectors so as to view only a limited (approximately 30 km across) region, uncertainties as to the size of the source region were reduced and X-rays from more distant precipitation regions were avoided.

With these improvements, X-ray spectra at balloon altitudes were corrected for absorption, giving the spectra at production altitudes. Results obtained in this way showed spectra of variable folding energies E_0, ranging from as low as 5 keV to

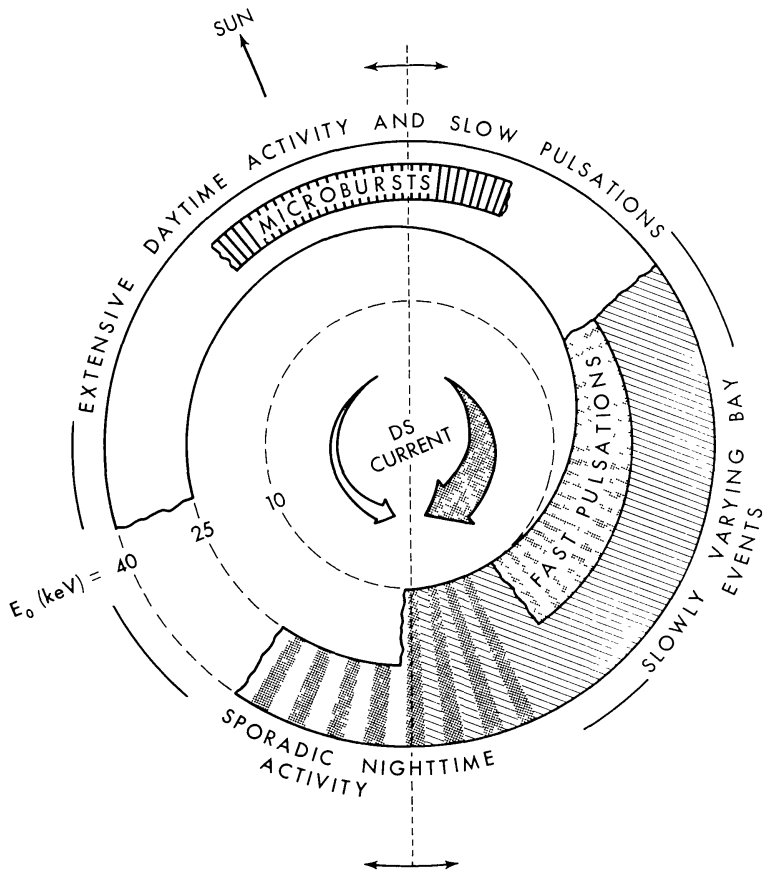

Fig. 2.18. Dirunal pattern of the spectral character of electron precipitation, as indicated by X-ray measurements. (BARCUS and ROSENBERG, 1966.)

somewhat greater than 30 keV. A comparison of spectrum determinations during a number of individual microbursts with the quiescent background spectrum of auroral X-rays showed that the microburst spectra did not deviate significantly from that of the background.

7. *Particle deposition*

Using calculations of the type indicated above, the electron influx over the auroral zone has been evaluated from X-ray observations within the atmosphere. The fluxes obtained were found to vary over a wide range, from small values ($\sim 10^5$ electrons/cm^2-sec) during times of magnetic quiet to modest values during bay events and finally to large values ($> 10^8$ electrons/cm^2-sec) during storm conditions. Taking power-law

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spectra ($\gamma \sim 5$) and considering X-rays above 30 keV, balloon data over several weeks of observation (ANDERSON, 1960; BROWN, 1960) gave values of the order of 10^{10} and 10^{11} electrons/cm^2 for the daily precipitation rate. While these results first came from experiments using Geiger counters, later flights of scintillation counters over a three-year period (ANDERSON, 1964) gave similar results. In terms of average electron flux above 30 keV, this amounts to 2×10^6 cm^{-2}-sec^{-1} and is in good agreement with the precipitated flux 2×10^6 cm^{-2}-sec^{-1} above 40 keV reported by O'BRIEN (1964) from satellite data.

Beyond these comparisons, the total number of energetic electrons precipitated into the auroral zone is of interest in that it may be compared with the number of radiation belt electrons trapped in the yoke-shaped volume having unit area at auroral latitude. From early estimates of the trapped electron flux, it appeared that the radiation belt supply would be adequate to account for the daily electron loss. However, with the downward revision (O'BRIEN *et al.*, 1962) of the outer zone fluxes, this idea has proved untenable, the trapped radiation failing to meet the observed demands by up to several orders of magnitude on occasions. For example, at auroral latitudes, the contents of a tube of force amounts to $3 \times 10^9 - 3 \times 10^{10}$ electrons/cm^2 (O'BRIEN, 1963); thus, an average flux of the order of 10^6 cm^{-2}-sec^{-1} could be maintained for only about 10^3 to 10^4 sec without exhausting the statically-trapped supply; however, this represents only a modest flux and more intense precipitation can extend over longer periods during strong geophysical disturbances.

Results of a similar nature were obtained by WINCKLER *et al.* (1962) in their latitude study during SC and GC magnetic storms. Here, it was found that the total energy precipitated at places of maximum intensity in a 10–12 hour period during the two magnetic storms was at one to two orders of magnitude more than that stored in trapped radiation, taken from outer-zone flux values.

An even more striking example of the insufficiency of trapped radiation in explaining electron precipitation is found in the intense X-ray event observed at Ft. Churchill, Canada by the Minnesota group in the summer of 1961. The X-ray burst occurred simultaneously with a negative excursion in the geomagnetic field during conditions of strong geophysical disturbance ($K_p = 6-$), the intense peak having a duration less than one minute and accompanied by a large absorption peak on the Ft. Churchill riometer. The peak flux was 5×10^5 photons/cm^2-sec and in 100 seconds the event yielded a total energy input into the atmosphere of 8×10^{12} keV/cm^2 above 60 keV; this is to be compared with 5×10^{10} keV/cm^2 above 60 keV in the static reservoir.

It has been argued that shortcomings of the reservoir hypothesis could be overcome by assuming that the particle influx is localized and the precipitation region supplied by the continuous eastward drift of trapped electrons from other parts of the reservoir. The large-scale character of electron precipitation, however, makes it difficult to invoke this idea in general. For specific instances where the energy input exceeds that held locally on field lines, this does represent a *possible* interpretation but only within limitations of the extent of the precipitation region. In particular, this alternative depends on the participation of a large number of tubes, each bringing its full comple-

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ment of particles to the precipitation region for release into the atmosphere. For an event of duration T, this is equivalent to requiring that the longitudinal extent L of the precipitation region be small compared to the distance electrons drift during this time:

$$L \ll \left(\frac{2\pi R_e \cos\lambda}{\tau_d}\right) T$$

where $2\pi R_e \cos\lambda$ is the circumference ($\sim 10^9$ cm) of the auroral zone and τ_d is the longitudinal drift period ($\sim 5 \times 10^3$ sec) of 50 keV electrons. For the event above, where the energy input over 100 seconds exceeded the trapped supply by more than two orders of magnitude, a precipitation region limited to a few kilometers across would be consistent with this approach.

This result, as well as others, pointed up the need for additional energization mechanisms. Thus, the early concept of the outer zone, providing only trapped radiation as the source of auroral zone effects, has given way to another model proposed by O'Brien (1962). Here, particles precipitating into the atmosphere are regarded as freshly accelerated particles and the radiation trapped in the geomagnetic field represents accelerated particles having pitch-angles such that they remain trapped when the accelerating disturbance has subsided. Hence, the "leaky bucket model" is to be replaced by the "splash catcher model".

While the examples cited above play down the role of the static reservoir, there still remains the possibility that it could contribute to *some* precipitation events of a suitable mechanism could be found. This point was made by Barcus (1965) in examining an intense nighttime X-ray event at Barrow, Alaska ($L=8$). In this instance, a pronounced hardening of the X-ray flux was noted with several high counting rate peaks. Such a hardening would be expected for precipitation events of sufficient intensity to make a near-maximum demand on the trapped supply of low-energy particles as higher energy particles drift at a faster rate, enabling a larger number of tubes of force to participate while the untrapping mechanism is operative.

Another example of electron precipitation perhaps within the resources of the trapped supply of radiation, in spite of being widespread in longitude, is the sudden commencement event. From X-ray observations, Brown *et al.* (1961) estimated that 3×10^9 electrons/cm^2 above 30 keV were precipitated into the atmosphere during the SC event of June 27, 1960; a demand of this magnitude is within the capabilities of the trapped reservoir (O'Brien, 1963). Additional data on SC events are badly needed, however, as only this one event has been examined to date; further, Hoffman *et al.* (1962) have reported a burst of low energy electrons (10–35 keV) on the sunward side beyond the Magnetosphere ($L=12$) in coincidence with a storm sudden commencement. The flux reached a peak level of 4×10^7 electrons/cm^2-sec and lasted only a few minutes, thus showing some resemblance to SC electron precipitation.

B. DISCUSSION

Undoubtedly, the unique contribution of X-ray observations at balloon altitude to the electron precipitation problem has been in establishing the temporal features of the

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electron influx; riometers, by their very nature, are too slow for most purposes while rockets and satellites move far too fast, spending little time in the precipitation regions. As a result, it has proved possible to sort out several types of electron precipitation events according to their temporal character and examine other aspects associated with them. For example, the major part of electron bombardment at auroral latitudes has been found to be unstructured in time. While it cannot be said that this always has the same nature, particularly in view of the range of energy spectra that it displays, it does represent one important form of the precipitation process. The evidence to date leads to the conclusion that it involves an acceleration mechanism, not merely a "dumping" which releases previously energized particles into the atmosphere.

From the morphology of ionospheric and magnetic disturbances accompanying this class of events, it is evident that the precipitation takes place on a large scale – covering many hundreds of kilometers in latitude at times, having smaller spatial structure within it, and extending thousands of kilometers in longitude, perhaps circling the entire auroral zone. In addition, conjugate studies at auroral latitudes indicate that similar activity takes place simultaneously in each hemisphere, details of the precipitation agreeing well for regions closely connected by lines of force. This circumstance argues strongly for a fairly symmetrical precipitation process with lines of force around $L=6$ remaining essentially intact in spite of the perturbing influence of solar plasma on the magnetosphere. This is in sharp contrast to the situation at higher latitudes, at both the front (CAHILL, 1963) and rear (HEPPNER *et al.*, 1963; NESS, 1965) of the magnetosphere where lines of force are compressed and dragged out, respectively.

Next, there exists the group of time variations which are superimposed on the smooth precipitation, ranging from long-period pulsations associated with hydromagnetic waves to short-duration microbursts. Over this range of time, from hundreds of seconds to hundreds of milli-seconds, there appears to be a division in the type of precipitation processes involved. Thus, long-period pulsations, down to about 75 seconds period, entail modest but significant modulation of the smooth electron precipitation already in progress; presumably, the mechanism involves the effect of compressional hydromagnetic waves on the size of the dumping cone (SINGH, 1964; BARCUS and CHRISTENSEN, 1965) of the "splash catcher". Like the steady precipitation process, pulsating events of this type show striking similarity in conjugate regions (BROWN *et al.*, 1965). While the amount of data is somewhat limited, there are indications (BARCUS and ROSENBERG, 1965; HOLT and BROWN, unpublished) that the scale of pulsating precipitation is fairly large, as would be expected from hydromagnetic modulation of extended electron precipitation, and it appears to display propagation effects as the hydromagnetic disturbances advance in the magnetosphere.

At a shorter time scale, from irregular pulsations of a few seconds spacing down to microbursts, different processes are required. Here, while time-structured precipitation may extend over considerable distance, it is coherent only over a limited area at auroral latitudes. For example, it has been found (BROWN *et al.*, 1965) that short-

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period pulsations and microbursts have a scale size of the order of 100 km or so at atmospheric heights. Taking this back along field lines to the equatorial plane gives a region the order of 10^3 km across, quite small compared to magnetospheric dimensions. Thus, it is difficult to envisage large-scale, propagating disturbances giving rise to these small-scale temporal features; rather, it would appear that conditions on a small scale, such as might be associated with plasma instabilities, serve as a source of these time-variations in the electron influx.

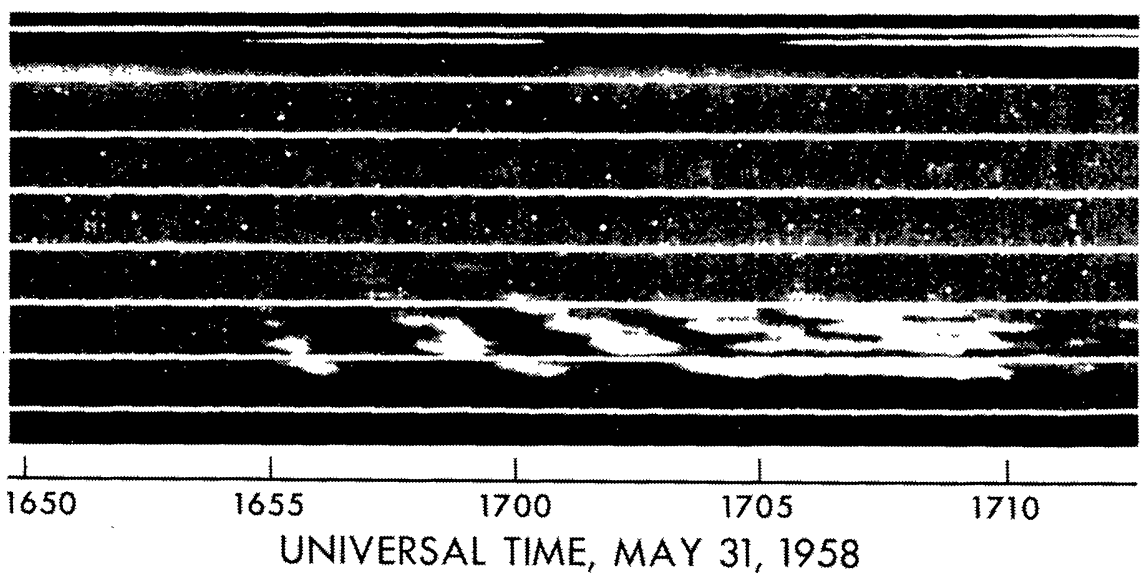

Fig. 2.19. Pulsating auroral radar echoes following an SC (1652 UT; May 31, 1958). The observations were made from Bluff, New Zealand, the antenna beams pointing toward Campbell Island. Zero range at the top of the figure and range marks are 200 km apart. (UNWIN and BROOKS, private communication.)

Considering the types of time variations in electron precipitation cited above and the fact that these were largely established on a firm basis after the observation of sudden commencement electron bombardment, there remains the possibility that this type of event may prove to be more structured than present results would indicate. This is particularly the case when note is made of the fact that SC measurements were obtained with low-resolution detectors (ionization chambers and Geiger counters) or under complex circumstances (nuclear gamma-ray contamination during a PCA event). In addition, studies of geomagnetic data (WILSON and SUGIURA, 1961) show pulsations after SC are similar to those accompanying precipitation events and radar observations (UNWIN and BROOKS, private communication) show pulsating echoes with the onset of sudden commencements as in Figure 2.19. This record, from the storm beginning at 1652 UT on May 31, 1958, points up another interesting aspect of SC precipitation: the echoes begin a minute or two after the SC and appear first on the equatorward side of the auroral zone. Thus, with features like this, further examination of this type of event may be rewarding, hopefully aiding in reaching an understanding of the transient precipitation process.

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In addition to these temporal features, there are other aspects of electron precipitation that X-ray studies have brought forward. One, for example, is the pronounced asymmetry in intensity of precipitation between the dawn and dusk meridians, also recognized from ionospheric absorption data. In simplest terms, precipitation in the evening hours is weak and featureless while that in the morning hours is much more intense and often highly structured. The origin of this striking feature ranks in importance with questions dealing with energization, spectra and time variations.

While X-ray observations support the idea of conjugacy in electron precipitation, the data to date apply only to the slow time variations. This raises the question of the extent to which this is true at shorter time scales. Experimental data shows pulsation activity simultaneously in both hemispheres but the detectors have not been close enough (<100 km) in conjugacy to examine if electrons reach the atmosphere simultaneously at both ends of lines of force down to the limit of resolution. This remains one of the most important questions to be explored further, particularly in that it should shed some light on details of the precipitation process.

3. Rocket and Satellite Studies

A. ROCKET RESULTS

Rocket experiments at auroral latitudes, although relatively few in number to date, have greatly extended the kinds of measurements made in connection with the electron precipitation problem. Thus, instead of relying on the indirect (and involved) arguments from ground-based observations, these studies have given straight-forward measures of the incident particle fluxes, the relative number of electrons and protons, energy spectra, angular distributions and other effects of the particle bombardment, such as ionization and luminosity profiles. This approach began when the pioneering flights using the rockoon technique (VAN ALLEN, 1957) carried detectors right into the particle beams, gas-filled counters and scintillation detectors behind the nose-cones essentially responding to bremsstrahlung from electrons impinging on the condensed material. The results obtained from these flights gave the first measurements on the geographical distribution of the radiation as well as the fluxes involved in the range from 10 to 100 keV or so.

In subsequent flights, the rocket nose-cones were removed from in front of the detectors after the rockets had passed through the denser portions of the atmosphere. Thus, MCILWAIN (1960) reported on flights where electron and proton detectors as well as a Geiger counter were exposed directly to the particle beams; in addition, rocket photometers were used to estimate the fraction of auroral light produced below the rockets throughout their flights. In this experiment, the electron detector was sensitive to particles with energies from 3 to about 100 keV while the proton detector, sweeping out electrons with energies less than 1 MeV by means of a "magnetic broom", responded to particles with energies from 45 to about 500 keV.

During two flights in February 1958, these detectors were fired into a faint aurora as well as a bright auroral arc over Ft. Churchill, Canada. In the faint display, the

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electron detector measured an energy flux of about 20 ergs/cm^2-sec and the proton-electron ratio was approximately 10^{-3}; for the bright arc, the energy flux was considerably higher, about 2×10^3 ergs/cm^2-sec, but the proton-electron ratio was lower than before.

Of particular interest are the electron energy spectra from these flights. For the flight into a faint auroral glow, the altitude dependence of the electron energy flux obtained from a Cs I(Tl) scintillation counter indicated that the observations could have been produced by electrons having an integral energy spectrum

$$N(\geqslant E) = 2.5 \times 10^9 \exp(-E/5) \text{electrons/cm}^2\text{-sec}$$

for energies E between 3 and 30 keV. This spectrum is considerably steeper than those mentioned in connection with balloon observations and was not accompanied by an increase in the counting rate of a Geiger counter in the rocket payload.

Results closely similar to these, both in electron energy flux and proton intensities, were obtained by DAVIS *et al.* (1960) in another rocket experiment. As such, they indicated that protons play only a minor role in the excitation of aurora and the principal effects arising in the lower ionosphere result from the incidence of electrons. This same argument was put forward earlier by OMHOLT (1959) on the basis of a comparison of H_β emissions with those from N_2^+ during aurora.

For the flight into the bright auroral arc, the electron energy spectrum was different from that measured in the faint auroral glow. Thus, instead of a particle spectrum covering a fairly wide range of energies, the electrons in the bright arc appeared to be nearly monoenergetic at about 6 keV with a peak flux of about 5×10^{10} electrons/cm^2-sec. Both these results point up the importance of low-energy electrons in steep spectra, the presence or absence of which are matters beyond the bremsstrahlung technique when working through thick layers of absorbing material.

By way of contrast, an example of a flatter electron spectrum was noted during rocket experiments by MCDIARMID *et al.* (1961). Here, the technique was to measure the atmospheric absorption of the electron flux above 30 keV by means of a Geiger counter and, using the exponential representation, a spectrum with an *e*-folding energy of 22 keV was reported during an auroral absorption event ($\sim$3 dB). This value is in the same range that balloon observations yield results and is close to the value ($E_0 \cong 25$ keV) reported by ANDERSON and ENEMARK (1960).

This experiment also gave some indications of the angular distribution of the electron flux relative to the geomagnetic field lines. Thus, taking variations of the counting rate due to the rocket spin in flight, MCDIARMID *et al.* (1961) pointed out three types of distributions: the first was isotropic for pitch-angles less than 90°, the second had a maximum at pitch-angles greater than 90° while the third appeared as a superposition of the first two with a minimum at about 90°. By way of explanation of these features, it was proposed that the incoming beams of electrons had nearly an isotropic distribution for angles less than 90° and that an ionospheric electric field, having a small component *upward* along the field and a larger component transverse

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to the field, caused the changes in the angular distribution at large angles by reflecting some particles upward that would have been lost in the atmosphere in the absence of the field.

In addition to giving direct measurements of the electron energy spectrum and angular distribution, this experiment provided one of the first opportunities of comparing ionospheric absorption calculated from a measured electron flux with that observed simultaneously by a ground-based riometer. Thus, McDiarmid *et al.* (1961) calculated the electron density profile during the absorption event, assuming the electron intensity was isotropic during the rocket flight; these results showed a peak density of $\sim 2 \times 10^5$ electrons/cm^3 at about 85 km altitude. The electron density due to secondary X-rays was also calculated and found to be somewhat more than two orders of magnitude lower than that for collisional ionization and centered around 70 km. A comparison of the calculated absorption with that recorded by the Ft, Churchill riometer (30 mc/s) gave only fair agreement with the experimental value. but still it showed that the observed flux of electrons above 30 keV was clearly sufficient to give rise to the observed absorption on this occasion.

Additional measurements of angular distributions and electron energy spectra from rocket flights in 1963 and 1964 were given by McDiarmid and Budzinski (1964). In these flights angular distribution data were obtained by collimating thin window Geiger counters inclined at various angles with respect to the rocket axes while energy spectra resulted from pulse height analyses of electron energy losses in Cs I(Tl) scintillation detectors; further, a current scintillator of Cs I was used to evaluate the electron energy input into the atmosphere above 4 keV.

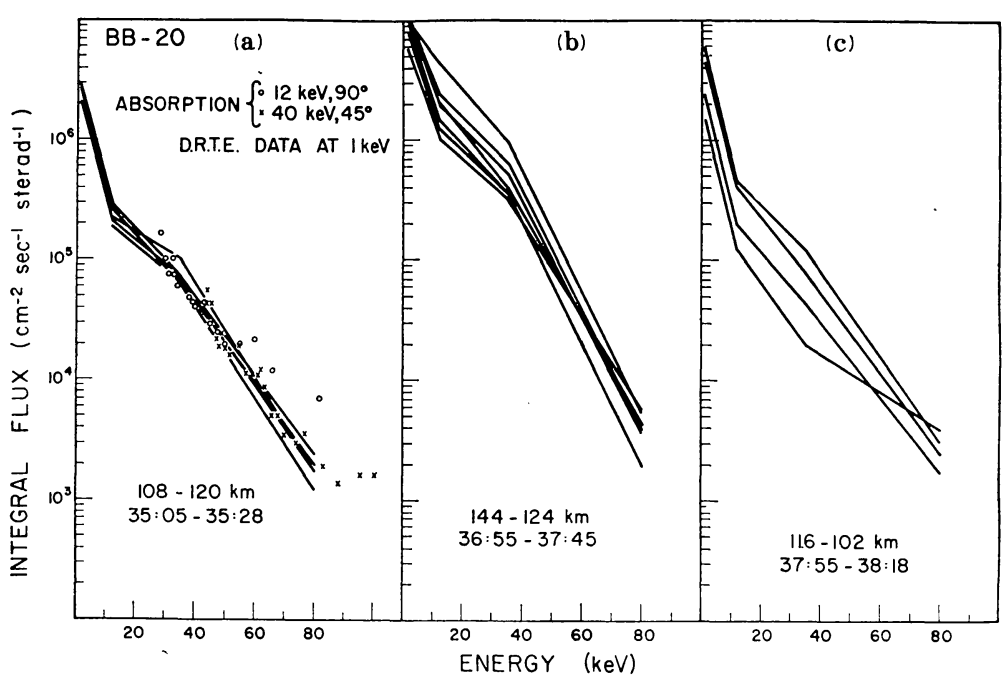

Fig. 3.1. Rocket observations of electron spectra during an auroral event. (McDiarmid and Budzinski, 1964.)

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Taking counting data from one detector, in the range 35 to 80 keV, integral energy spectra were obtained; typical spectra could be represented by an exponential form with an *e*-folding energy of about 12 keV. However, it was pointed out that the electron energy spectrum can vary greatly with time, particularly at the lower energies, as shown in Figure 3.1 where data extend down to about 1 keV.

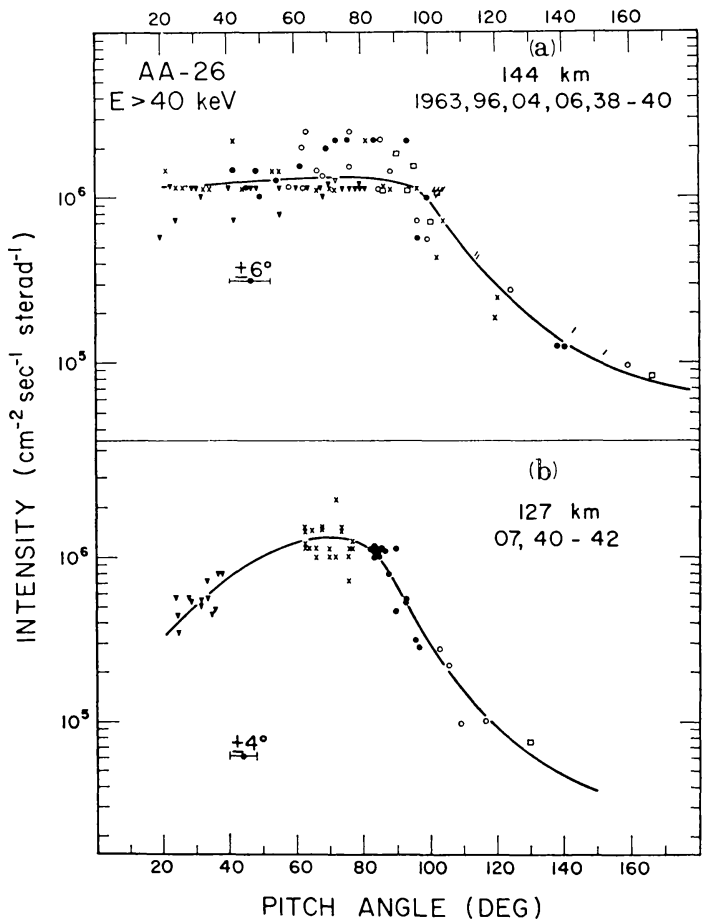

Fig. 3.2. Examples of angular distributions of electrons during an auroral event. (McDiarmid and Budzinski, 1964.)

The pitch-angle distributions obtained in this series of flights showed varying degrees of isotropy for angles less than 90°. For altitudes between 100 and 150 km, distributions ranged from almost complete isotropy to essentially no isotropy, with little indication of the relation between intensity and the nature of the angular distributions. Examples of the types of distributions observed during an intense auroral event are shown in Figure 3.2. These were taken at two altitudes, approximately one minute apart in time, and show first (a) an isotropic distribution at angles less than 90° and followed then (b) by a distribution where the intensity falls off at smaller angles. The difference between these two distributions is pointed up by noting that essentially the same intensity was recorded around 90° at both times.

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The angular distributions reported from this flight series extended out to values from 120° to 180° with respect to the field and none of the distributions observed showed more particles traveling upward than could be accounted for by backscattering. Further, no angular distribution was observed in which the intensity increased towards small angles.

For these rocket flights, a somewhat different use was made of the spectral data in connection with the auroral absorption problem. In particular, electron production rates (q) as a function of height were calculated and compared with simultaneous electron densities (N) from r.f. probe measurements made at the same time; in this way an altitude profile of the effective recombination coefficient of the atmosphere

$$\alpha_{\text{eff}} = q/N^2$$

was obtained and compared with the nighttime values of CRAIN (1961). This showed a rough agreement for altitudes above 82 km but large discrepancies deeper in the atmosphere. The recombination profile of CRAIN (1961) took into account collisional detachment of electrons from negative ions at night; with the indications that collisional detachment is essentially negligible (REID, 1965), some of the discrepancies at lower altitude may be less difficult to understand.

More recent rocket flights have used other techniques in studying electron precipitation. Thus, RIEDLER (1965) employed semi-conductor detectors in a rocket payload flown in Norway to examine electron fluxes above 40 keV. For an auroral absorption event of about 1.5 dB, fluxes of $\sim 10^6$ electrons/cm^2-sec-ster above 40 keV were encountered, with exponential e-folding energies from 5 keV to 20 keV. On this flight, a rocket-borne photometer showed a strong auroral emission peaking with the electron influx; with the increasing luminosity, the lower energy part of the electron spectrum hardened while the higher energy portion became steeper.

In another rocket experiment, EVANS (1966) has examined low-energy electron fluxes associated with an auroral display by means of magnetic spectrometers utilizing channel electron multipliers (EVANS, 1965). Launching into the breakup of an aurora (100 kR luminosity, 3.2 dB absorption at peak), the rocket measurements were made during the decaying phase (40 kR, 1.3 dB absorption) of the display. The rocket data showed an intense precipitation event in progress (the electron flux above 25 keV exceeded 10^9 electrons/cm^2-sec-ster and the electron spectrum hardened, with the e-folding energy increasing from 20–35 keV to greater than 50 keV over the energy range from 3.5 keV to 25 keV, at peak). The peak electron flux obtained during this flight is comparable with extreme values reported from balloon observations (BHAVSAR, 1961) and recent satellite data (MCDIARMID and BURROWS, 1965) at high latitudes. Responses of the detectors in the rocket payload to the rapid onset of an increase in the electron influx indicated a time delay in the arrival of low energy (3.5–6 keV) electrons relative to those of a few hundred keV, similar to the velocity dispersion reported by ANDERSON and MILTON (1964) during microburst events seen by X-ray detectors at balloon altitude.

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B. SATELLITE RESULTS

The early satellite experiments were instrumented with the aim of mapping out features of trapped radiation rather than examining aspects of the electron precipitation problem in the auroral zone. However, with the initial flights taking place close to the maximum of activity in the last solar cycle, a number of strong geophysical disturbances were encountered and with observations available from within as well as beyond the atmosphere, the first ideas linking processes in the radiation zone and those at the top of the atmosphere were developed. For example, ROTHWELL and MCILWAIN (1960), studying changes in intensity of trapped particles measured with Geiger counters on Explorer IV, noted marked decreases in intensity during magnetic storms in late 1958. These decreases were observed at altitudes above 1000 km, at the fringes of the outer radiation belt; at lower altitudes under the outer zone, intensity increases were found. These results suggested that particles trapped at higher altitudes were scattered down, by atmospheric heating and expansion during magnetic storms; as such, the observations supported the idea that trapped radiation served as a reservoir, providing the particles to produce geophysical disturbances.

A further instance of an intensity decrease in the outer radiation zone was reported by ARNOLDY *et al.* (1960) from observations with an ionization chamber and Geiger counter on Explorer VI during a geomagnetic storm in August, 1959. Using the satellite data on the changes in the number of electrons in the radiation zone, on the assumption that the satellite detectors were responding to bremsstrahlung from low energy ($\sim$50 keV) electrons, a comparison was made with the number of electrons required to produce auroral X-rays during similar magnetic storms. The approach suggested that more than enough radiation was lost from the outer zone to account completely for the X-ray bursts. In addition, by comparing the intensity profiles of the outer zone, before and after the magnetic storm, it was concluded that most of the radiation was lost between geomagnetic latitudes 52° and 62°, with a peak intensity around 57–58°. This location was consistent with many X-ray observations and agreed with the observation of a strong aurora at approximately 57° latitude during the particular magnetic storm.

Another type of correlation between radiation intensity measured in the outer zone (Explorer VI) and geophysical disturbance, supporting the hypothesis that the outer zone served as a reservoir, was reported by O'BRIEN *et al.* (1960). Here, very intense zones of radiation appeared to be correlated in space and time with a visible aurora at about 55° geomagnetic latitude. Energy considerations, based on an early estimate of the electron flux at satellite altitude, were given that suggested there was sufficient energy flux to excite the aurora, thus making the correlation more than just qualitative.

While these results pointed to the trapped radiation as a likely source of geophysical effects at sub-auroral latitudes, especially during magnetic storms, riometer and balloon observations showed that significant electron precipitation was taking place quite frequently in the auroral zone, far more so than at lower latitudes. Thus, some

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indications of difficulty appeared in connection with the reservoir idea because of the latitude profile in precipitation. These problems did not become acute until the matter of absolute electron fluxes in the outer zone came under close scrutiny. In this connection, the early interpretation of satellite results (VAN ALLEN, 1959) attributed the counting rate profiles of the particle detectors to bremsstrahlung from low energy electrons, with fluxes of the order of 10^{11} electrons/cm^2-sec for energies above 20 keV in the heart of the outer zone. With an analysis (DESSLER and VESTINE, 1960) of the maximum energy that could be stored in the geomagnetic field, DESSLER (1960) critically reviewed the omni-directional electron flux values, indicating that the particle energy density in the heart of the outer zone would exceed the magnetic energy density there unless the flux values were reduced by 1–3 orders of magnitude.

Prior to this time, the contents of a tube of force, having a cross section of 1 cm^2 at the top of the atmosphere, appeared adequate to account for the precipitation of electrons into the auroral atmosphere, at least for periods of the order of 10^5 seconds. However, such a downward revision in flux would change the whole scheme, making it questionable that the trapped radiation could fulfill the requirements of X-ray observations within the atmosphere.

The answer to this problem was not long in coming; O'BRIEN *et al.* (1962a), examining the results obtained with detectors on Explorer XII which responded directly to electrons below 100 keV showed that the first interpretation was incorrect. Thus, the fluxes in the outer zone, based on bremsstrahlung considerations with low detection efficiencies, had to be revised downward to lower values due to penetrating electrons recorded with detection efficiency close to unity. When this was done, the early flux values, $\sim 10^{11}$ electrons/cm^2-sec above 20 keV, were replaced by values of the order of 10^5 electrons/cm^2-sec above 1 MeV or so, changing the whole character of the previous observations and interpretations of results.

Such a correction also touched on the latitude profile of the radiation zone as ROSSER *et al.* (1962) showed from Explorer XII data that low energy (>40 keV) electrons were present with fluxes ($\sim 10^7$–10^8 particles/cm^2-sec) of nearly constant intensity out to radial distances of 10–12 earth radii. Also, the trapping region for low energy particles showed a sharp outer boundary. In this connection, the high latitude boundary was studied by MAEHLUM and O'BRIEN (1963) with detectors on Injun 1. Here, it was found that the boundary was quite sharp and moved equatorward with magnetic storms, the electron spectrum becoming softer as the boundary was approached. Variations in the location of the trapping region boundary and magnetic indices (K_p) during one magnetic storm are shown in Figure 3.3.

Another satellite (Injun 1), with detector capabilities comparable to Explorer XII, was launched with the aim of orienting it with respect to the geomagnetic field throughout its flight, thus offering a means of obtaining direct data on the flux of low energy electrons at various pitch angles. While the desired orientation was not achieved, the magnetic sensor on board provided continuous data on detector alignment, thus indicating whether particle fluxes were trapped or precipitating into the atmosphere.

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For particles moving at small angles relative to the field, of interest to the electron precipitation problem, the results from Injun 1 showed that the electron energy spectrum was quite variable. An interesting example, reported (O'BRIEN *et al.*, 1962b) in some detail, was a daytime event of precipitating electrons with an energy flux of about 1 erg/cm^2-sec-ster above 40 keV, represented by a power-law spectrum with exponent $\gamma = -3$. From a total energy detector, sensitive above 1 keV, it was indicated

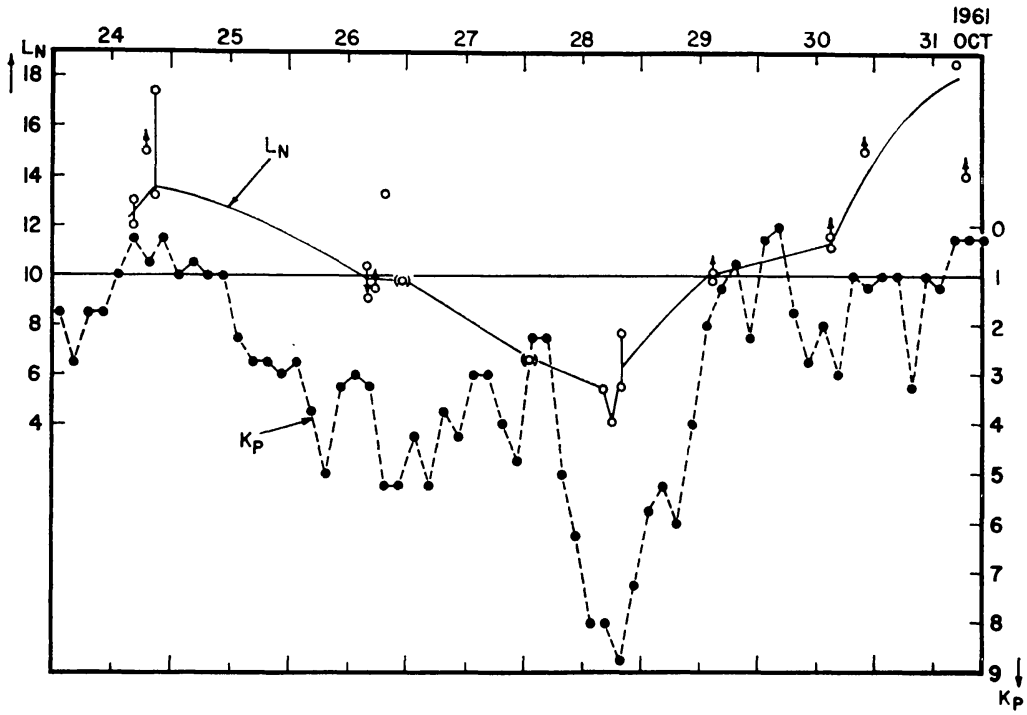

Fig. 3.3. Variations in the location of the trapping region boundary and magnetic K_p indices during a magnetic storm. (MAEHLUM and O'BRIEN, 1963.)

that the energy flux was 10 ergs/cm^2-sec-ster, corresponding to about 10^8 electrons/cm^2-sec-ster. This event is comparable in energy input to those investigated by DAVIS *et al.* (1960) and MCILWAIN (1960), thus indicating that it was capable of producing a weak auroral display.

O'BRIEN *et al.* (1962b) stressed that the Injun1 data showed large variations in intensity and spectral character for precipitating fluxes, suggesting that the power-law spectrum with $\gamma = -5$, first due to VERNOV *et al.* (1959) and used widely in interpreting balloon X-ray data, is not always valid. Further, while precipitating fluxes $\gtrsim 4 \times 10^6$ particles/cm^2-sec-ster greater than 40 keV were encountered, these values overlapped only the lower electron fluxes inferred from X-ray data. While there was strong possibility that the interpretation of X-ray data may have over-estimated the electron fluxes, O'BRIEN *et al.* (1962b) did not rule out the possibility that Injun 1 encountered only modest events during the period studies (July–August, 1961).

Observations of lower energy electrons precipitating over auroral forms were reported by SHARP *et al.* (1964) from measurements on an oriented polar orbiting

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satellite. Because of technical difficulties, these were limited to measurements by total energy detectors with thresholds at 2 keV and 28 keV. On three passes over Alaska, both detectors responded, giving rough determinations of the energy distribution in the incident flux. One pass through a homogeneous auroral arc showed a peak intensity of about 10^8 electrons/cm^2-sec-ster above 2 keV, with an exponential folding energy $E_0 \sim 8$ keV. The most intense event had a peak flux of 8×10^9 electrons/cm^2-sec-ster above 2 keV, corresponding to an energy input (~ 100 ergs/cm^2-sec-ster) sufficient to excite an IBC III aurora and comparable to the value reported by McIlwain (1960) at rocket altitudes. Here again, the particle flux above 28 keV accounted for only a minor fraction of the total incident energy ($E_0 \sim 5$–8 keV). These precipitation regions were fairly broad and showed a smooth variation; however, cases were found in which regions of precipitation were well separated, with other regions between them where the particle intensity was below the sensitivity of the detectors.

The Injun 3 satellite achieved the magnetic orientation first attempted with Injun 1, thus placing an array of detectors distributed about the local magnetic field vector so that both precipitating and trapped electron fluxes could be studied *simultaneously*. Using primarily measurements from three directional Geiger counters, as shown in Figure 3.4, O'Brien (1964) summarized the results obtained relative to the electron flux as a function of geomagnetic latitude, longitude and magnetic disturbance. Of particular interest to the precipitation problem were the observations that showed the intensity of electrons mirroring at satellite altitudes increases rather than decreases

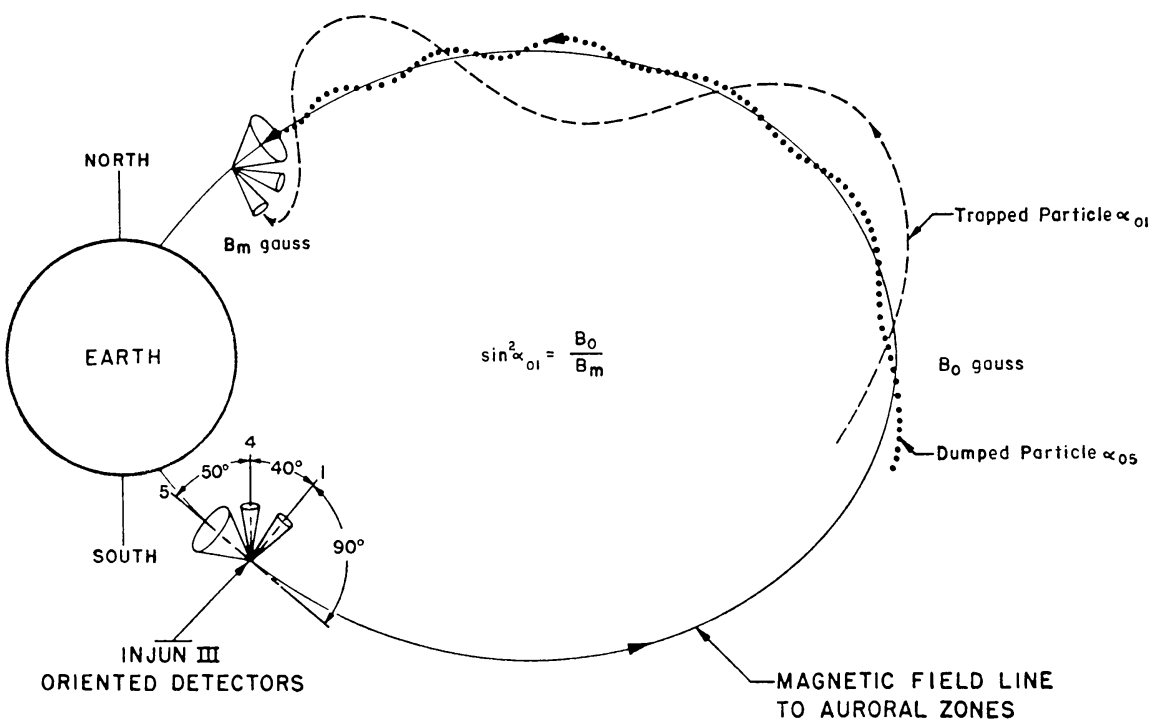

Fig. 3.4. The arrangement and use of Geiger counters on the magnetically-oriented satellite Injun 3. (O'Brien, 1964.)

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when precipitation occurs. An illustration of this is shown in Figure 3.5 where it is seen how both the trapped and precipitating fluxes increased as the satellite passed over an aurora, indicated by the response of the auroral (3914 Å) photometer on board. This serves to support the splash-catcher model rather than the leaky-bucket model as in the splash-catcher model (O'BRIEN, 1962) the radiation zone flux is expected to *increase* as the processes precipitating electrons are also taken to be responsi-

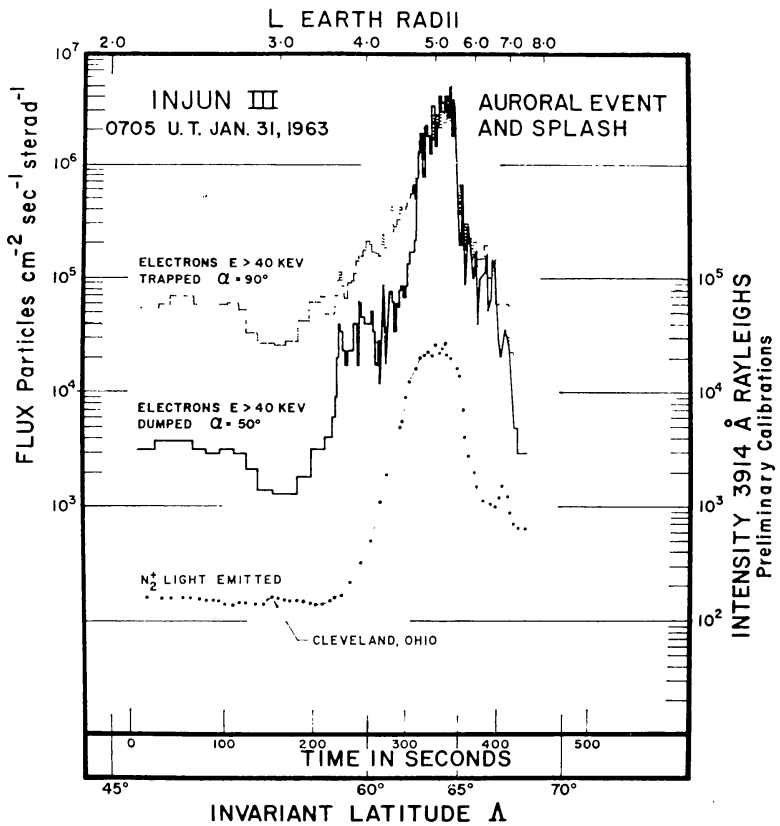

Fig. 3.5. Observations of the variation trapped and precipitated electron fluxes as well as auroral luminosity during a satellite pass. (O'BRIEN, 1964.)

ble for adding to the contents of the trapping region while in the latter case the flux of trapped particles would be expected to *decrease* as the electrons drain out of the radiation zone to cause the aurora below.

Injun 3 data showed that precipitation is generally more intense during strong magnetic activity, as indicated by the planetary index K_p. This is illustrated by Figure 3.6 where magnetic indices and precipitating flux values are given for auroral latitudes ($L \sim 6$). In a more general sense, the flux of precipitating particles above 40 keV shows a stronger variation with K_p than trapped fluxes, as shown by a statistical comparison of Injun 3 and Explorer XII data in Figure 3.7.

With the high orbital inclination (70°) of Injun 3, it provided information on the latitude profile of precipitation from $L=2$ to $L=33$. These measurements showed a large scatter in the precipitating fluxes at a given L value, reaching a million to one

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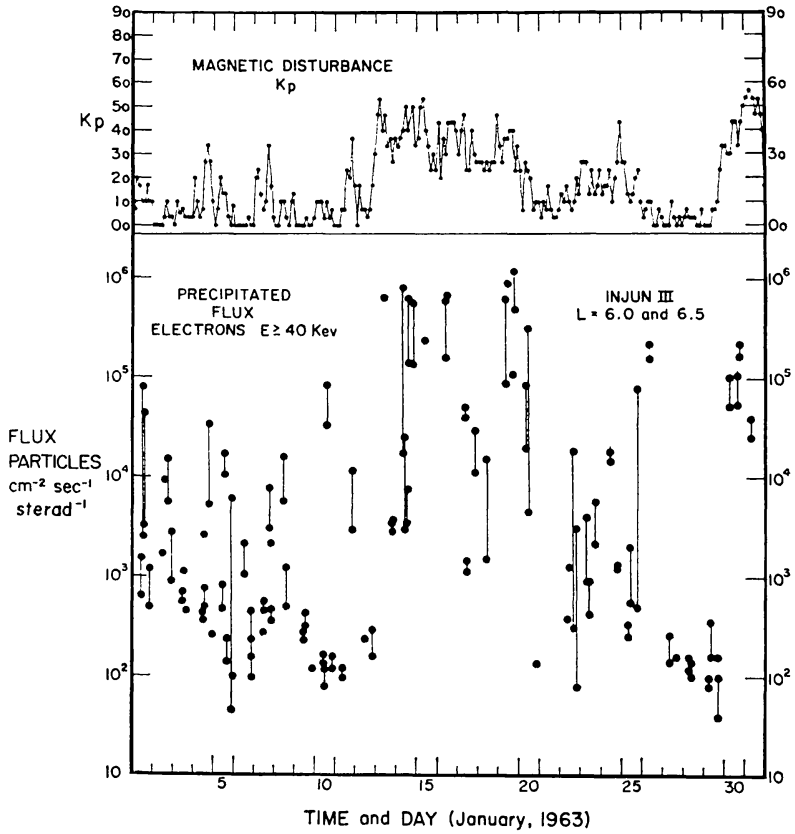

Fig. 3.6. Variations in precipitated electron flux at $L = 6.0$ and 6.5 with planetary magnetic index K_p. (O'Brien, 1964.)

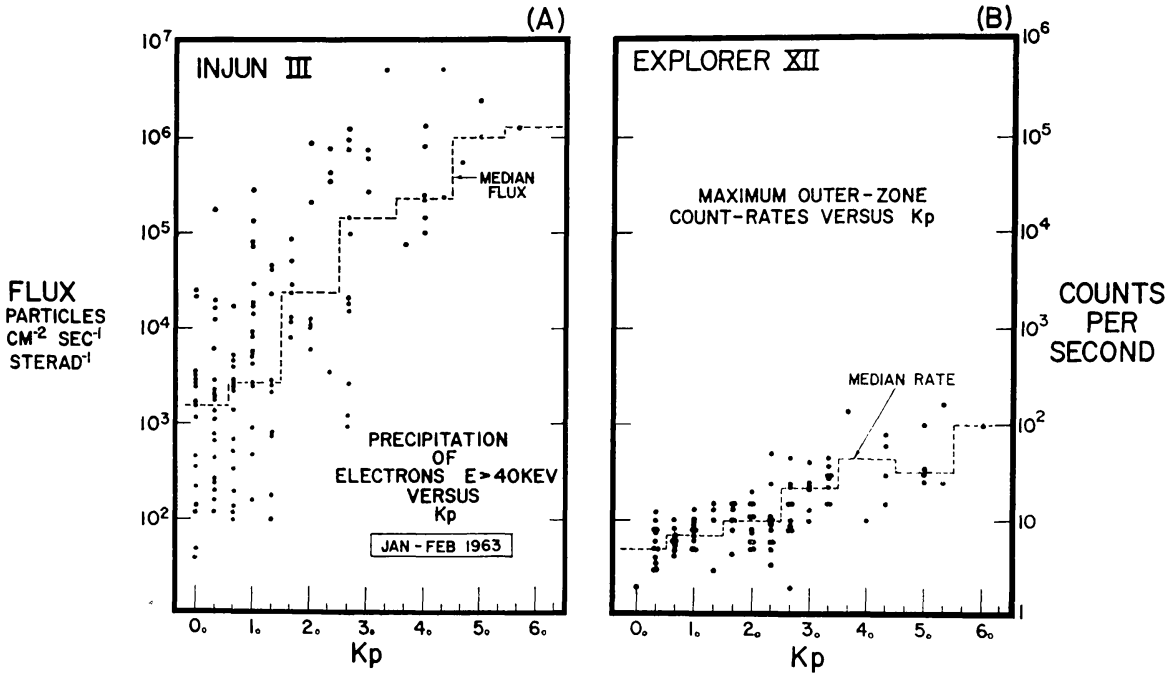

Fig. 3.7. Variations in the flux of precipitated (A) and trapped (B) electrons with K_p. (O'Brien, 1964.)

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in the auroral zone. With such a large range of variation, it is difficult to determine meaningful average values but an indication of the behavior of the precipitating fluxes is given by typical values of the order of 10^2 to 10^3 electrons/cm^2-sec-ster at mid-latitudes ($L \sim 2$), increasing rapidly to $\sim 10^5$ electrons/cm^2-sec-ster in the auroral zone and then decreasing at higher latitudes.

In the course of measuring precipitating fluxes with Injun 3, the detector arrangement made it possible to make simultaneous measurements of the directional flux at two pitch-angles with respect to the field, α and $180° - \alpha$. Thus, comparisons were made of the downward, precipitating flux to the upward, back-scattered flux; this showed that approximately 10% of the precipitating particles were back-scattered. Since no instances were found where the upward flux exceeded the downward flux, it was concluded the region where processes are responsible for precipitation is located well above the satellite's position.

In addition to having a large dynamic range, the detectors on Injun 3 also had a high time resolution. Thus, it was possible to follow fast changes in the particle intensity, although a separation as to spatial and temporal features was difficult because of the rapid satellite motion. In this connection, it is interesting to note that one of the large, rapid intensity variations noted in the Injun 3 data, shown in Figure 3.8, resembles the time structure of auroral zone X-rays. Since the satellite

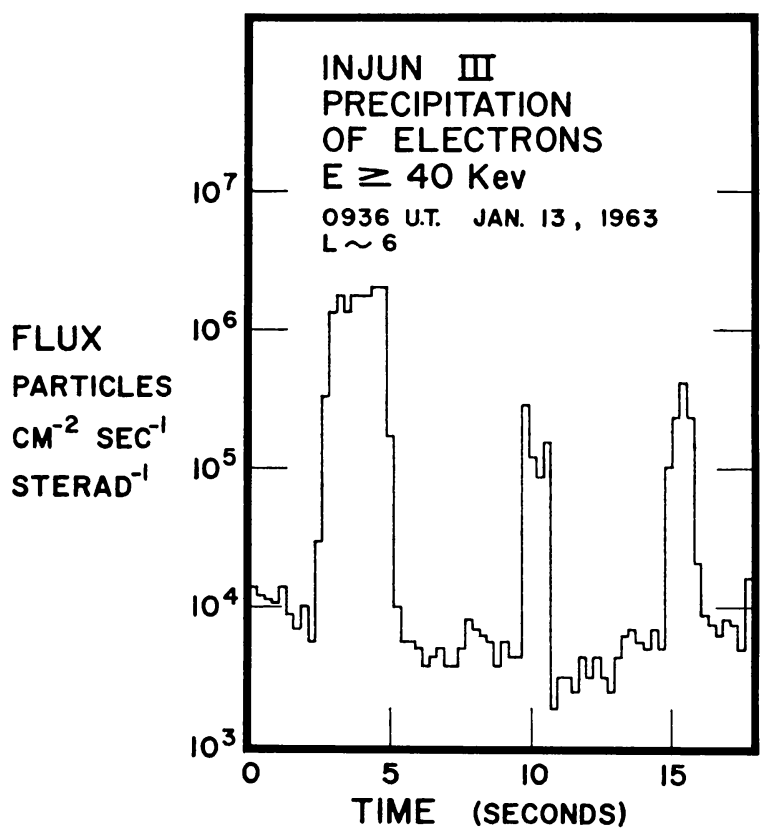

Fig. 3.8. Large variations in electron precipitation over a short time interval. (O'Brien, 1964.)

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motion over this interval was about 100 km, the scale size of fast pulsating X-ray events, it is quite possible that the variation was of a temporal nature.

While details of the energy spectrums (LAUGHLIN *et al.*, to be published) from Injun 3 were not given by O'BRIEN (1964), a brief summary of the spectral characteristics were included in the Injun 3 results. Of particular interest to the electron precipitation problem are the results on spectral variability. Here, it was found that the energy spectrum below 100 keV was highly variable, with time and/or space, in a given precipitation event, the spectrum appearing generally softer toward higher magnetic latitudes. In addition, from optical emissions accompanying electron precipitation it was concluded that, on occasions, the flux of electrons around 10 eV energy was no larger than those with about 10 keV, indicating that the energy spectrum below 10 keV does not always continue to rise with the same slope as at higher energies.

The relationship between electron fluxes at satellite altitudes and auroral absorption within the atmosphere has been examined by MAEHLUM and O'BRIEN (1963), JELLY *et al.* (1964) and PARTHASARATHY *et al.* (1965). Thus, MAEHLUM and O'BRIEN (1963) began by using Injun 1 data for electrons above 40 keV and riometer records over North America. This study showed the existence of a high latitude boundary for quasi-trapped particles which moved equator-ward with increasing magnetic activity. Riometer data during the same period showed that the maximum ionospheric absorption was found just below the boundary, even when it moved about. This relationship between trapped fluxes and ionospheric absorption pointed toward a connection between trapped and precipitating fluxes.

JELLY *et al.* (1964) examined the same relationship with precipitating electron fluxes measured by detectors on the Alouette I satellite. Using data from satellite passes within five degrees longitude of the riometer locations, this study showed that without appreciable fluxes of electrons precipitating into the atmosphere, there is little in the way of absorption and vice-versa. Comparisons of precipitating fluxes and riometer data showed that the average relationship between these quantities agreed approximately with theory; however, spectral information was not available from Alouette I so that the scatter of data points could not be examined in more detail. By way of indicating the sort of magnitudes involved, for the most intense auroral absorption event ($\sim$10 dB at 27.6 mc/s) the satellite detectors showed that the precipitating flux was about 8×10^6 electrons/cm^2-sec-ster above 40 keV. In addition, for equal fluxes of particles, the riometer data suggested that the day-night absorption ratio was about 2, as shown in Figure 3.9.

More recently, PARTHASARATHY *et al.* (1965), using simultaneous measurements of trapped and precipitating fluxes from Injun 3 data, compared ionospheric absorption values at College ($L=5.5$) and Ft. Yukon ($L=6.3$), Alaska with satellite data. On occasions, when precipitation was occurring more or less isotropically over the upper hemisphere, this study gave an empirical relationship

$$A\,(\mathrm{dB}) = 3.3 \times 10^{-3} \sqrt{N(>40\,\mathrm{keV})}$$

between the two sets of data. The experimental values on which this was based are

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shown, in part, in Figure 3.10. Measurements at longitudes closer to the riometer sites were available but did not materially improve the correlation between the data. By way of interpretation, the relationship given above was found to be consistent with ionization effects resulting from electrons with a spectrum of the form

$$\frac{\mathrm{d}N}{\mathrm{d}E} = KE^{-4.5}\,\mathrm{d}E$$

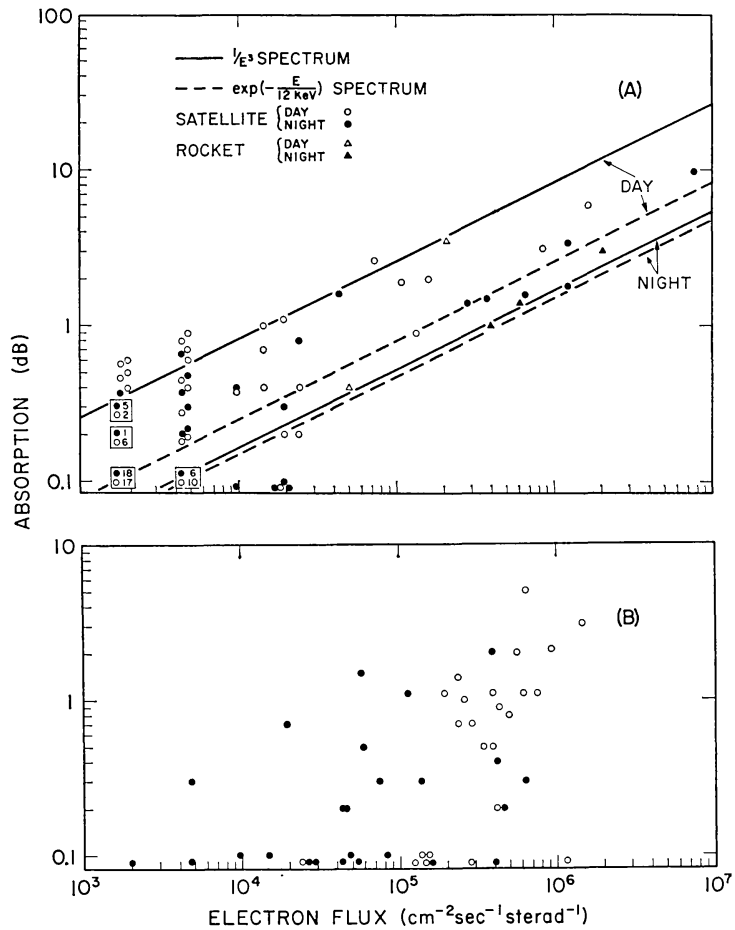

Fig. 3.9. The relationship between precipitated (upper) and trapped (lower) electron fluxes at satellite altitude and auroral absorption within the atmosphere. In the upper figure, the calculated dependence is given for flat (E^{-3}) and steep (12 keV folding energy) electron spectra for both day and night. (Jelly *et al.*, 1964.)

JELLY *et al.* (1964) used both a hard (E^{-3}) power-law and a soft ($\exp(-E/12$ keV)) exponential differential spectra for a similar comparison but the scatter of data points, shown in Figure 3.9, was too great to draw definite conclusions between the two calculations.

The latitude variation of trapped and dumped electrons, such as shown in Figures 3.11 and 3.12, have taken on greater importance, particularly at high magnetic latitudes on the night side of the earth, now that the magnetospheric tail has been established (NESS, 1965). While it is too early now to see how this will fit in with the

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features of the radiation zones developed to date, it has taken the focus of attention off of the lower latitudes and placed it on auroral latitudes and beyond.

In this connection, it is interesting to note that Alouette 1 data (McDiarmid and Burrows, 1965) has yielded examples of very intense particle fluxes in the tail of the magnetosphere, reaching values of $\sim 10^9$ electrons/cm^2-sec-ster above 40 keV. These

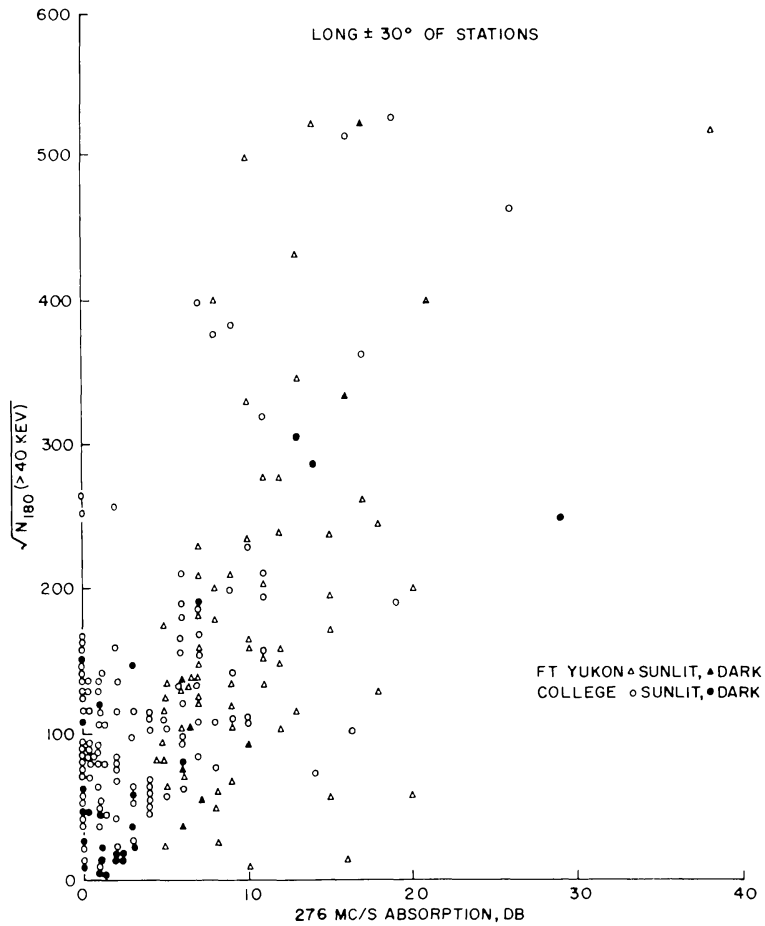

Fig. 3.10. Cross-plot of the square root of the precipitated electron flux above 40 keV and auroral absorption at 27.6 mc/s. (Parthasarathy *et al.*, 1965.)

fluxes range up to three orders of magnitude greater than those reported (O'Brien, 1962b) from Injun 1 surveys in the same regions. McDiarmid *et al.* (1965) have argued that these electrons go to populate the outer zone. However, such fluxes may also be connected with precipitation phenomena at high magnetic latitudes. In this connection, it is interesting to note (Barcus, private communication) that one of the intense high latitude electron spikes (1002 UT, March 10, 1963) reported by McDiarmid and Burrows (1965) coincides very closely in space and time with an intense X-ray burst (Figure 3; Barcus, 1965) over Pt. Barrow, Alaska ($L \sim 8$). Further, since all-sky camera records for this event showed a poleward motion of the auroral forms, there is the distinct possibility that transport into the trapped radiation zones is not the only fate open to these particles beyond the usual trapping region.

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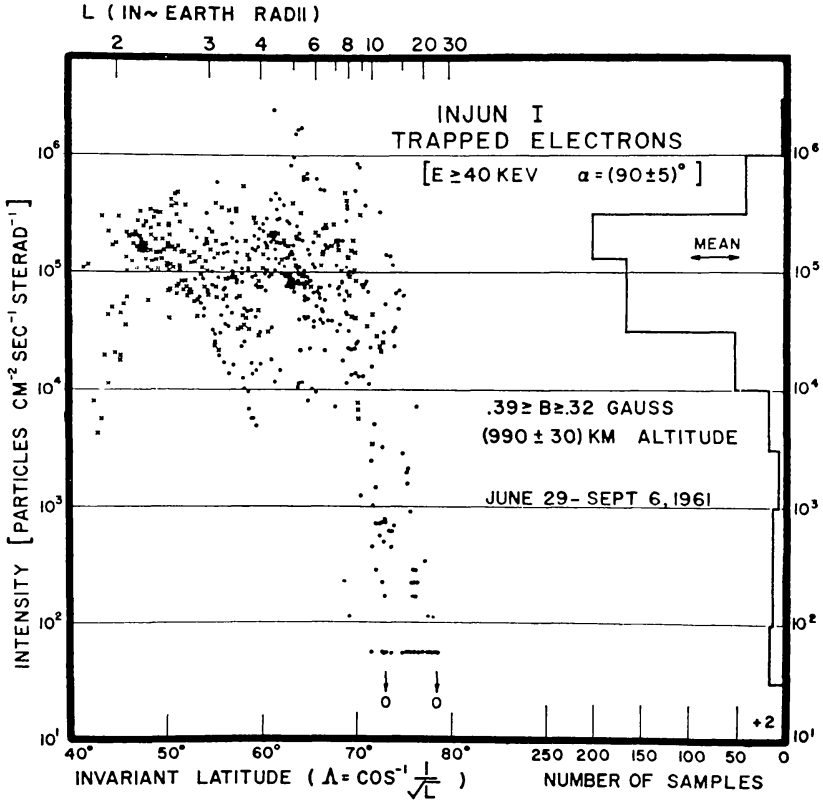

Fig. 3.11. The latitude variation of trapped electron intensity above 40 keV. (O'Brien, 1962b.)

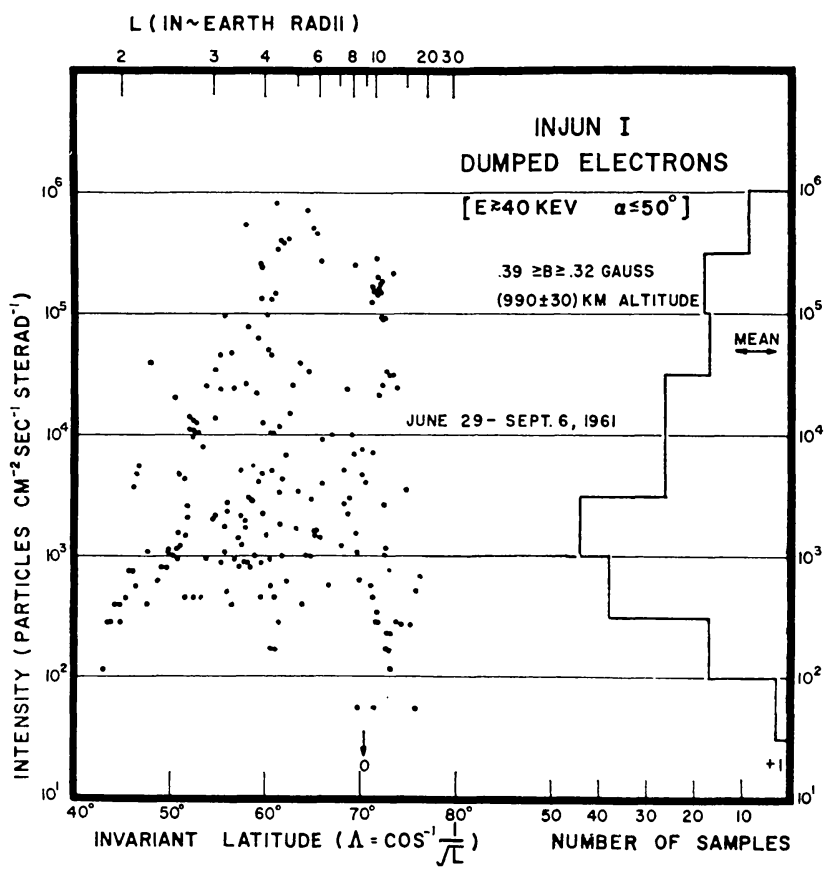

Fig. 3.12. The latitude variation of precipitated electron intensity above 40 keV. (O'Brien, 1962b.)

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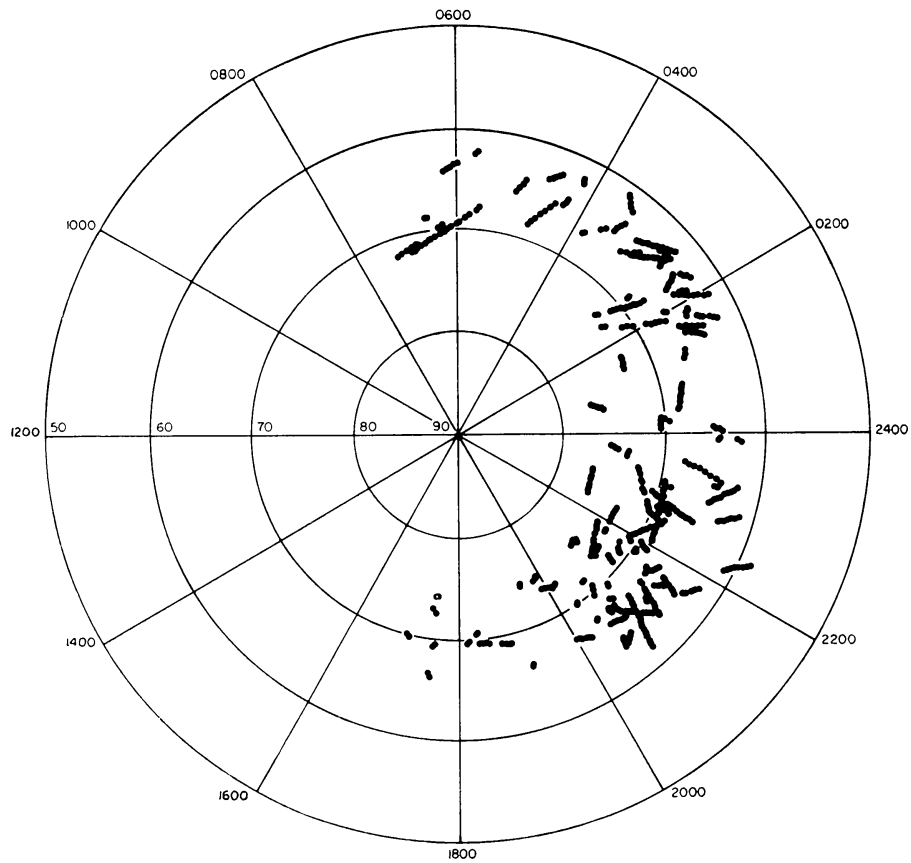

Fig. 3.13. Polar plot of the occurrence of electron fluxes above 10 keV as a function of geomagnetic time and latitude. (FRITZ and GURNETT, 1965.)

Other aspects of electron fluxes at high latitudes have been brought forward by FRITZ and GURNETT (1965). Here, working with an electron multiplier on Injun 3 which was sensitive to electrons above 10 keV, it was found that a strong diurnal effect was present. Thus, large fluxes of low energy electrons were found during local magnetic nighttime, with enhancements of magnetic activity over the range of from 58° to 76° latitude as shown in Figure 3.13. With the presence of these electrons a strong spectral change was observed, the energy spectrum between 10 and 40 keV changing from relatively "flat" below the trapping boundary to extremely "steep" above the boundary.

C. DISCUSSION

The information on electron precipitation in the auroral zone obtained by rocket and satellite techniques differ considerably – in scope, detail and resolution. Thus, rockets have provided a means of exploring individual precipitation events for a short span of time, yielding data on particle fluxes and spectra, of interest in their own right as well as for comparison with other ground-based observations. Considering the wide range of precipitation activity, structured in time or otherwise, it is clear that only a minute fraction of the problem has been scrutinized to date by rocket experiments. In

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spite of this fact, however, rocket probing of the incident electron beam has offered the best means of examining the effects produced by electron bombardment and it will continue to enjoy this position throughout the next solar cycle.

Satellites, on the other hand, have provided a broader view of electron precipitation, giving measures of the particle influx and crude spectrum measurements as well as geographical aspects of the phenomena. Hopefully, better experimental methods will be developed soon that will permit more definitive measurements at lower energies and more of a range in flux values so that more meaningful spectra can be obtained. The channel multiplier technique (EVANS, 1965) offers great promise in this regard.

Undoubtedly, the most exciting prospect for future investigations of electron precipitation in the auroral zone is that involving geo-stationary satellites ($L \sim 6.5$). With a full complement of conjugate ground-based equipment – rockets, riometers, balloon-borne detectors, all-sky cameras, photometers and magnetometers – as well as satellite instrumentation, the order-of-magnitude status of this problem would be improved rapidly. Since the technical capability for such a program has existed now for several years, it only remains to be carried out. Hopefully, it will be in the forseeable future.

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