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# AURORA AND THE LOWER IONOSPHERE IN RELATION TO SATELLITE OBSERVATIONS OF PARTICLE PRECIPITATION

by

Bengt Hultqvist*
Goddard Space Flight Center
Greenbelt, Maryland

## ABSTRACT

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The direct observations of electron precipitation by means of rockets and satellites is reviewed. Upon comparison of the observed energy fluxes with those expected on the basis of optical measurements of aurora, the agreement is found to be good. It is demonstrated that the satellite observations make understandable the observed variable degree of correlation between visual aurora and auroral absorption of radio waves. The precipitated electrons contribute significantly to the night time ionosphere not only in the auroral zone but also over the polar caps and in sub-auroral latitudes. It does not seem impossible that the observed precipitation of electrons is the main source of the nighttime ionization in the lower ionosphere. The airglow is briefly discussed in relation to observed particle precipitation. Finally, the recent demonstrations of the insufficiency of the Van Allen belt as a source for the precipitated electrons is briefly reviewed.

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*NASA—National Academy of Sciences—National Research Council Senior Post-Doctoral Resident Research Associate on leave of absence from Kiruna Geophysical Observatory, Kiruna, Sweden.

# AURORA AND THE LOWER IONOSPHERE IN RELATION TO SATELLITE OBSERVATIONS OF PARTICLE PRECIPITATION

## Introduction

The first rocket investigations of particles precipitated into the atmosphere were made by the Iowa group in the early 1950's. In IGY and thereafter a few more direct rocket measurements of high energy particles in auroral altitudes have been reported. Although of extreme value as exploratory studies, these few rocket measurements suffer from the weakness of being very limited in space and time. Some data about the rate of precipitation of electrons having energies greater than about 25 kev have been obtained from balloon observations of x-rays, but it is only in the last two years that systematic satellite measurements of precipitated particles, primarily by the two Injun satellites (O'Brien, 1962, a, b, 1964) and Alouette (McDiarmid, et al., 1963) have provided statistical data, on the basis of which some rough estimates of the average influence on the ionosphere can be made. In addition to precipitated electrons Injun 3 also measured the emission rate below the satellite of 3914Å and 5577Å photons along the magnetic field line upon which the satellite was located. The measurements have recently given very valuable information about detailed relations between electron precipitation and photon emission rate (O'Brien and Taylor, 1964).

One primary purpose of this review is to summarize some of the knowledge about relations between particle influx into the atmosphere and the resulting aurora and ionospheric effects. It should be said, however, that most reports on satellite observations published hitherto concern particles of fairly high energies (greater than 40 kev for electrons). For particles in the lowest energy range (i.e., from a fraction of 1 kev for electrons and some tens of kev for protons) the available experimental results are still scanty. What is going to be said about the influence of observed precipitation on the ionosphere above 100 km will therefore be most preliminary.

## Observations of Precipitated Electrons

The early rocket measurements (e.g., Davis et al., 1960; McIlwain, 1960) as well as the satellite results (e.g., O'Brien, 1962a, 1964) have verified the conclusions of Omholt (1957, 1959), based on spectroscopic observations of aurora, that the protons play a very minor role in the

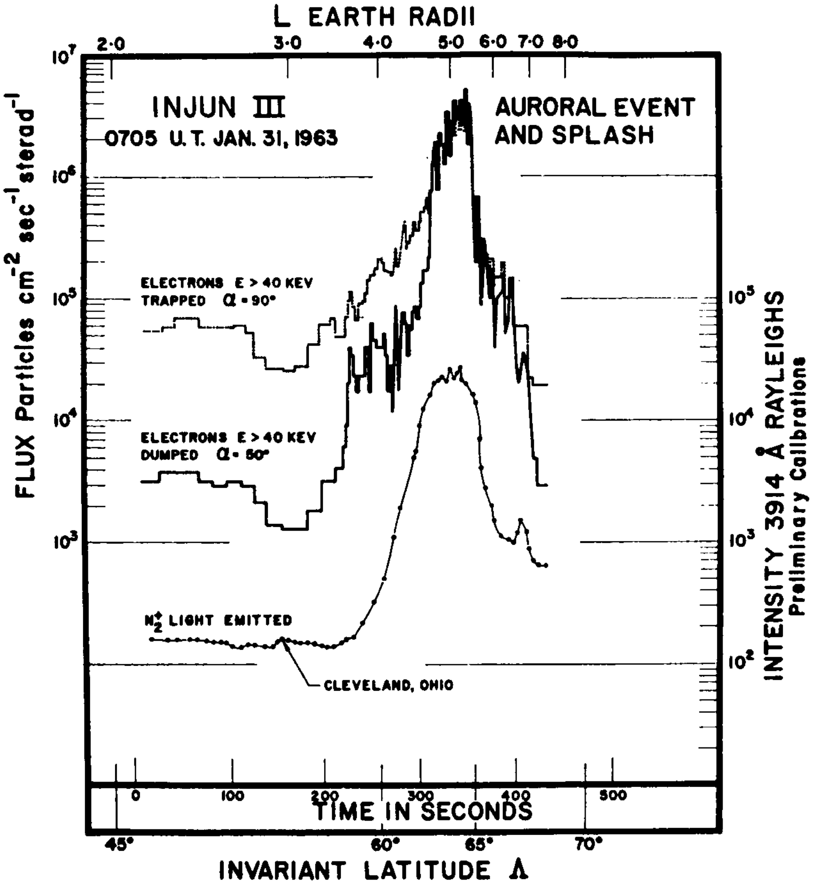

Figure 1 - Data from a northbound pass of Injun 3 over North America, which shows simultaneous detection of an aurora, of the precipitated electrons (with pitch angle 50°) partially responsible for causing it, and of trapped electrons. Note the approach to isotropy of the particle flux over the aurora, No attempt has been made to subtract the low-altitude contamination of the photometer signal, part of which was the detection of Cleveland, Ohio, and its surroundings. (After O'Brien and Taylor, 1964)

excitation of most aurorae and in producing ionization in the lower ionosphere. Therefore only electrons will be discussed in this review.

The first somewhat detailed satellite studies of particles that were definitely precipitated into the atmosphere were made by means of Injun 1 (O'Brien, 1962a, b). O'Brien and others working with satellite data define precipitated particles as those particles which would mirror at or below 100 km alitutde (if the atmosphere had not been present).

### (a) Latitudinal Distribution and Other Spatial Characteristics

The recent simultaneous measurements on Injun 3 (O'Brien and Taylor, 1964) of flux of precipitated electrons and of auroral light emission below the satellite have shown that above aurorae there are electron fluxes several orders of magnitude larger than outside the aurora. (Fig. 1).

Fairly extensive statistical data on the spatial characteristics of precipitated electrons have recently been published by O'Brien (1962a, b, 1964) and McDiarmid et al. (1963). Figure 2 shows the scatter diagram of the Injun 3 observations of precipitated electrons of energy above 40 kev for the range of the invariant latitude $\Lambda$ (defined by $\Lambda = \cos^{-1}(1/\sqrt{L})$ and at the most a few degrees different from geomagnetic latitude in the latitude range of interest here) between 45 and 76 degrees. As can be seen from the figure, the precipitated flux of electrons of $E \gtrsim 40$ kev has a broad maximum of about $10^5$ electrons/cm$^2$ sec ster for $\Lambda$ between 60 and 70 degrees. The flux is 2-3 orders of magnitude lower in subauroral latitudes. Figure 2 also shows that some 10 degrees inside the auroral zone the precipitation rate is down by 1-2 powers of ten.

Similar results have been found by McDiarmid et al. (1963) for electrons of energies above 40 kev and above 250 kev. Figure 3 shows their data presented in a manner different from that of O'Brien (1964). The histograms give, for two different ranges of magnetic activity, the percentage of passes in which the intensity of precipitated electrons with $E \gtrsim 40$ kev was above $1.5 \cdot 10^4$ electrons/cm$^2$ sec ster (corresponding to 0.2 db absorption at about 30 Mc/s). The flux of $1.5 \cdot 10^4$/cm$^2$ sec ster was one half of the maximum average intensity for $K_p < 4$ and 1/20 for $K_p > 4$. Figure 3 shows that during quiet geomagnetic conditions the precipitated intensity was greater than half the average value during some 25% of the passes through $\Lambda = 65°$, while for moderately disturbed conditions — there were no strong storms represented in the data — the intensity exceeded 1/20 of the average value in about 72% of the passes over that latitude.

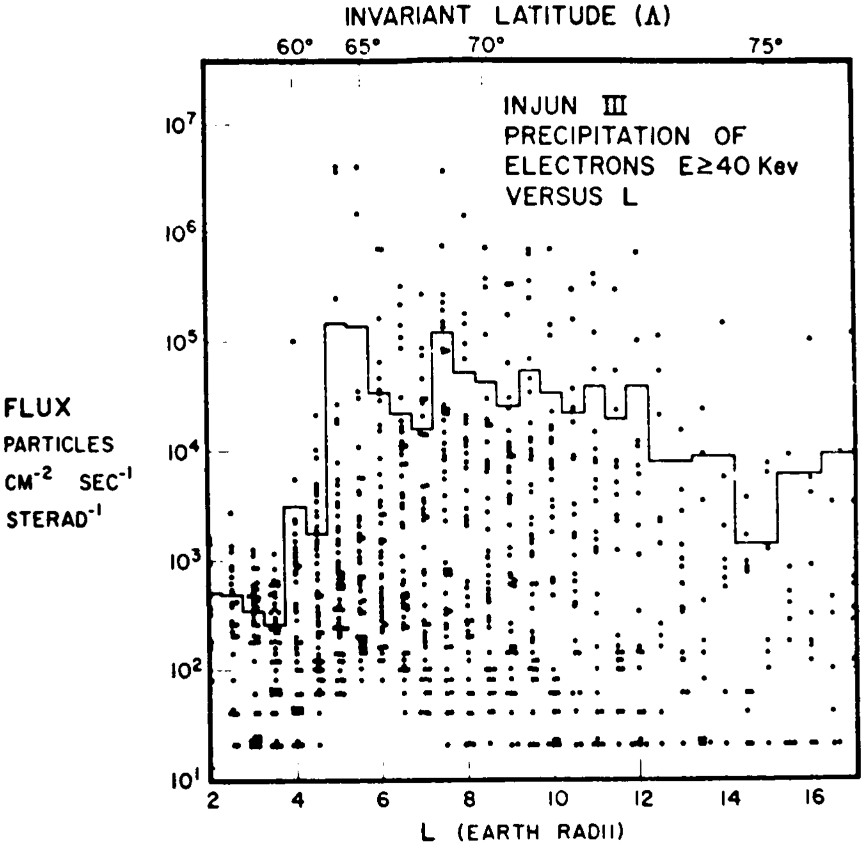

Figure 2 - Samples of precipitated fluxes over North America in January 1963. Each point is an 8-sec average of thirty two measurements made at half-integral values of L. The solid line gives the average flux. (After O'Brien, 1964)

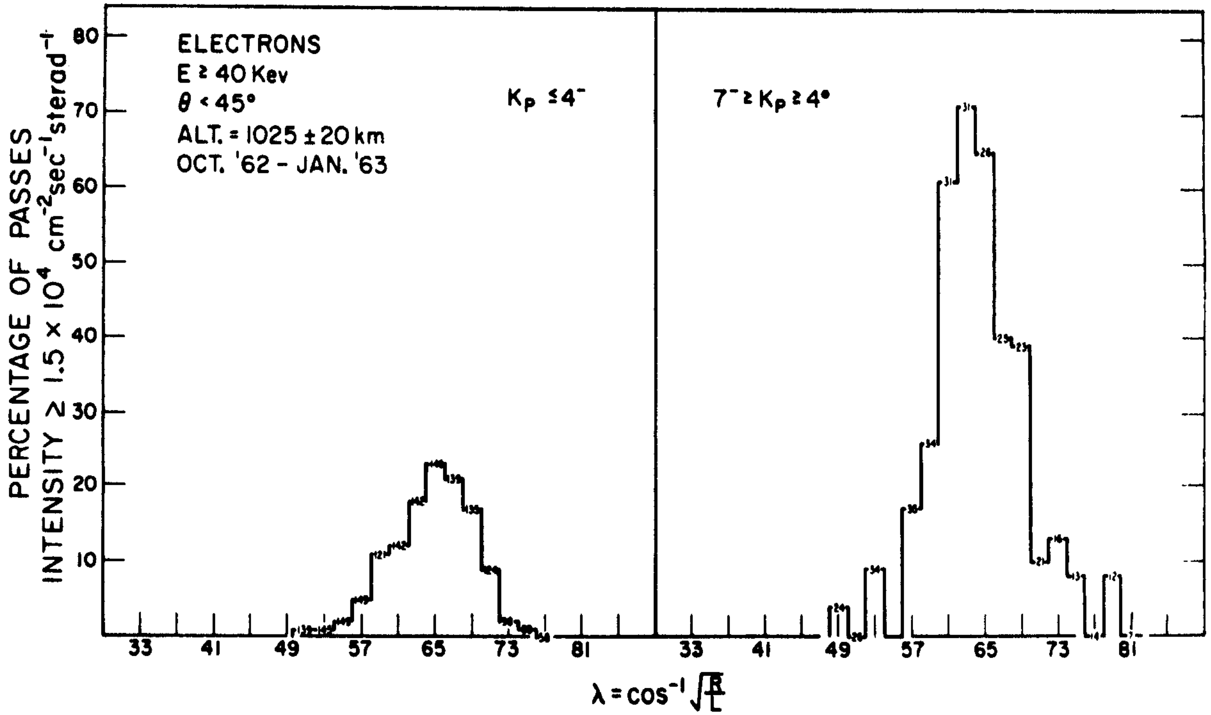

Figure 3 - Percentage of passes in which the intensity of precipitated electrons with energies greater than 40 kev was greater than 1.5 x $10^4$ $cm^{-2}$ $sec^{-1}$ $sterad^{-1}$ corresponding to 0.2 db of 30 Mc/s absorption, plotted against invariant latitude. (After McDiarmid et al., 1963)

Simultaneous observations on two satellites indicate that at least sometimes the area of precipitation has a fairly limited longitudinal extent (O'Brien and Laughlin, 1962). On the other hand the precipitated flux seems on occasions to be uniform over as much as 80 degrees of longitude, i.e., over more than 4000 km (O'Brien, 1964).

The latitudinal extent of the precipitation can be very restricted (e.g., over a range of $L \sim 1$ earth radius) or very extensive (over an L interval $> 20$ earth radii). This is illustrated in Figure 4.

The flux of precipitated electrons has its maximum close to the poleward boundary of the region of trapped electrons, as observed on the same satellite (McDiarmid et al., 1963; O'Brien, 1964).

Electron precipitation occurs simultaneously in magnetically conjugate areas at least sometimes, according to balloon observations of x-rays (Brown et al., 1963). This is in accordance with observations of aurora (cf. e.g. DeWitt, 1962).

A 100 fold change in the flux over two km has often been observed by Injun 3 which is in agreement with results of rocket measurements in aurora by Davis et al. (1960). They found the electron flux being concentrated in the visible auroral forms whereas protons were found over a much larger volume than that occupied by the aurora.

The statistical latitude profile of the intensity of dumped electrons with $E \gtrsim 40$ kev has been found by O'Brien and Taylor (1964) to have its maximum at a few degrees lower latitude than the frequency of occurrence of visual aurora as observed on the same satellite. Sometimes the visual emission has been found to extend to higher latitudes than the precipitation of electrons with energy greater than 40 kev, indicating electrons of $E < 40$ kev are being precipitated up to higher latitudes than the higher energy ones. The lower latitude limit of the aurora coincides with the lower latitude limit of appreciable precipitation (O'Brien, 1964; O'Brien and Taylor, 1964).

Precipitation was found all the time in the auroral zone by Injun 3 (O'Brien, 1964). It can be seen in Figure 2 that at $L = 6$ there was never observed any flux lower than about 80 electrons $(\text{cm}^2 \text{ sec ster})^{-1}$.

The corresponding continuous photon emission in the auroral zone is evident from Figure 5. The minimum emission rate is, however, below visual threshold even in the auroral zone.

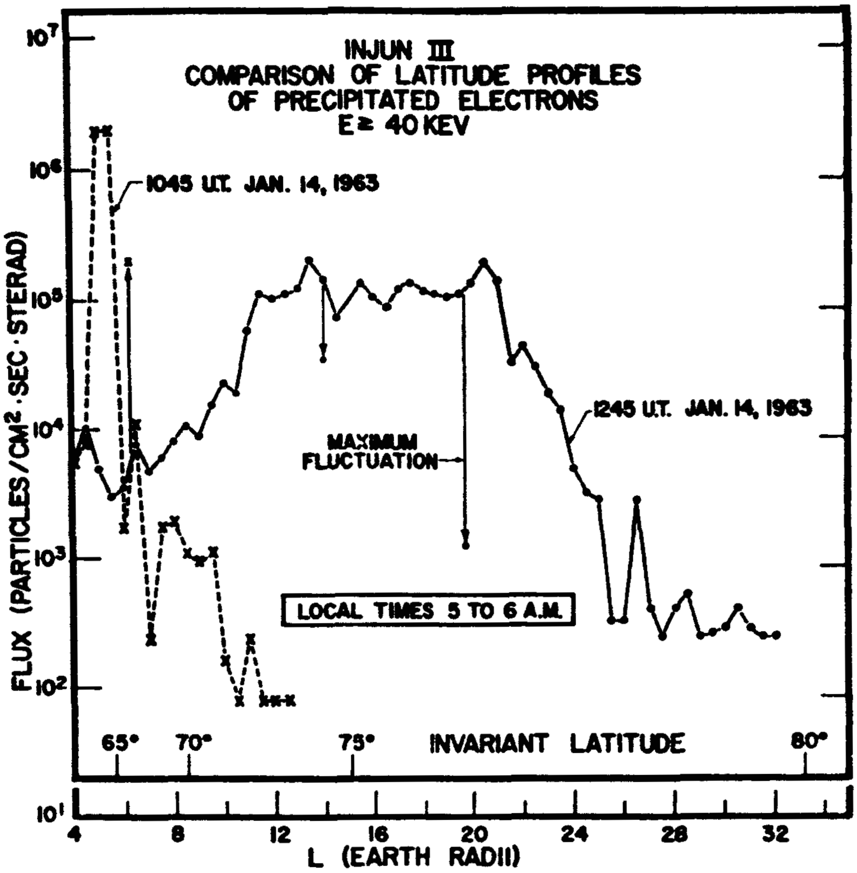

Figure 4 - Comparison of the latitude, or L profile, of precipitation for two successive passes at about the same local time. Arrows illustrate range of fluctuation of intensities at given locations. (After O'Brien, 1964)

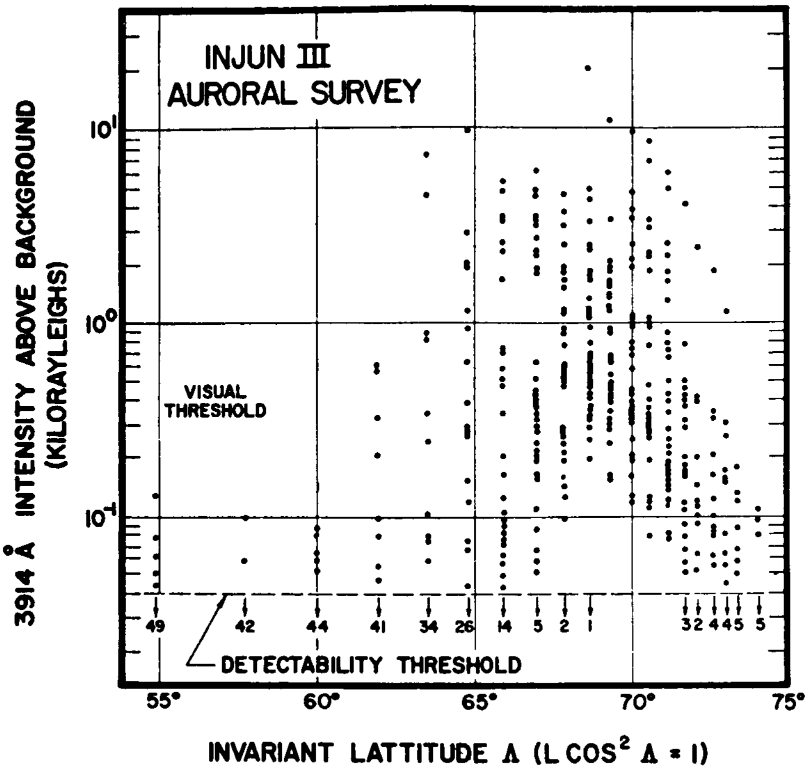

Figure 5 - Intensity of 3914Å auroral light average 4 sec at half-integral values of L in about fifty passes of Injun 3 early in 1963. (After O'Brien and Taylor, 1964)

Figures 2 and 5 also give a good impression about the enormous variability of precipitation and photon emission at all latitudes, but especially near the auroral zone. At L = 6 there are values of about $6 \cdot 10^6$ electrons/$cm^2$ sec ster shown in the figure. This is some $10^5$ times the minimum value observed there.

### (b) Time Characteristics of Precipitation

It is not possible in satellite measurements to differ between space variations and time variations short compared to the period of revolution. Balloon observations show, however, that time variations as rapid as of periods of a tenth of a second can occur in the electron flux (Winckler et al., 1962).

No systematic variation in the intensity of electron precipitation over periods as long as a day could be found by O'Brien (1964) from the Injun 1 and 3 measurements in contrast with the case for trapped electrons. Sharp et al. (1964) observed a higher nighttime than daytime precipitation flux of electrons in the energy range 0.08—24 kev—as well as of protons—during the 5 days life time of an oriented polar-orbiting satellite. They also found the energy distribution of the electrons to be harder on the dayside than on the nightside of the earth (Johnson et al., 1964). The Iowa group has recently reported the existence of a diurnal variation in the precipitated flux of electrons of energy above 40 kev at high latitudes. The maximum in the diurnal variation curve was reported to be on the dayside of the earth (Frank et al., 1964). It is not clear if the difference in the results found by various observers is due to the diurnal variation being different for different energy ranges or if it is due to some of the results being not statistically significant because of the enormous variability of the precipitation phenomenon.

### (c) Pitch Angle Distribution

Figure 1 shows that over the aurora, where the precipitation is intense, the directional flux of precipitated electrons becomes equal to the flux of trapped electrons, which also is increased over the aurora. Figure 1 illustrates a general rule that has been found by O'Brien (1962a, b, 1964), namely that for electrons of $E \geq 40$ kev the pitch angle distribution approaches isotropy in the regions of intense precipitation. An isotropic pitch angle distribution in regions of strong precipitation has also been observed by Krasovskii et al. (1962) at an energy of about

10 kev. No cases have been found in which the directional flux of precipitated electrons was higher than the corresponding value for trapped electrons. The mentioned observations were made fairly close to the earth's atmosphere.

The tendency to isotropy seems to indicate that the acceleration of the electrons—if it is directed along the field lines—takes place far away from the atmosphere. This, as well as the mentioned observations of precipitation of electrons from above 1000 km in aurorae, suggest that the role of the ionosphere in the production of the energetic electrons is not important.

O'Brien (1964) found a flux upwards along the field lines, which was some 10% of the precipitated electron flux. He interpreted these observations as backscattering of electrons from the atmosphere.

### (d) $K_p$ — Dependence of Precipitation

The $K_p$ dependence of the precipitation of electrons of energy above 40 kev is illustrated in Figure3. The average intensity was ten times higher near the auroral zone when $K_p$ was above 4 than when it was below 4. The data material for the higher $K_p$ range in Figure 3 does not contain data from any strong magnetic storm, so still higher values may be expected.

O'Brien (1964) found that the flux of precipitated electrons above 40 kev increased on the average by a factor of 5 for every step of $K_p$. A close correlation between precipitation intensity has also been observed for the 0.08—24 kev energy range by Sharp et al. (1964). O'Brien's results, obtained on Injun 3 in a low orbit, are shown in Figure 6 together with the dependence of the omnidirectional flux above 40 kev as observed in the equatorial plane far from the earth by Explorer 12 (Freeman, 1963). As can be seen, the $K_p$ dependence is very much larger close to the earth (at one end of the field line). If one assumes that both increases are due to a common acceleration mechanism it follows that it acts preferentially parallel to the geomagnetic field lines (O'Brien, 1964).

The change of omnidirectional flux above 40 kev with $K_p$, shown in Figure 6b, is opposite to what has mostly been observed for electrons of $E \gtrsim 2$ Mev (Arnoldy et al., 1960; Hoffman et al., 1962).

The dependence of the poleward boundary of precipitation on magnetic activity has been studied by Maehlum and O'Brien (1963). They used data for trapped electrons, but since O'Brien (1964) has shown

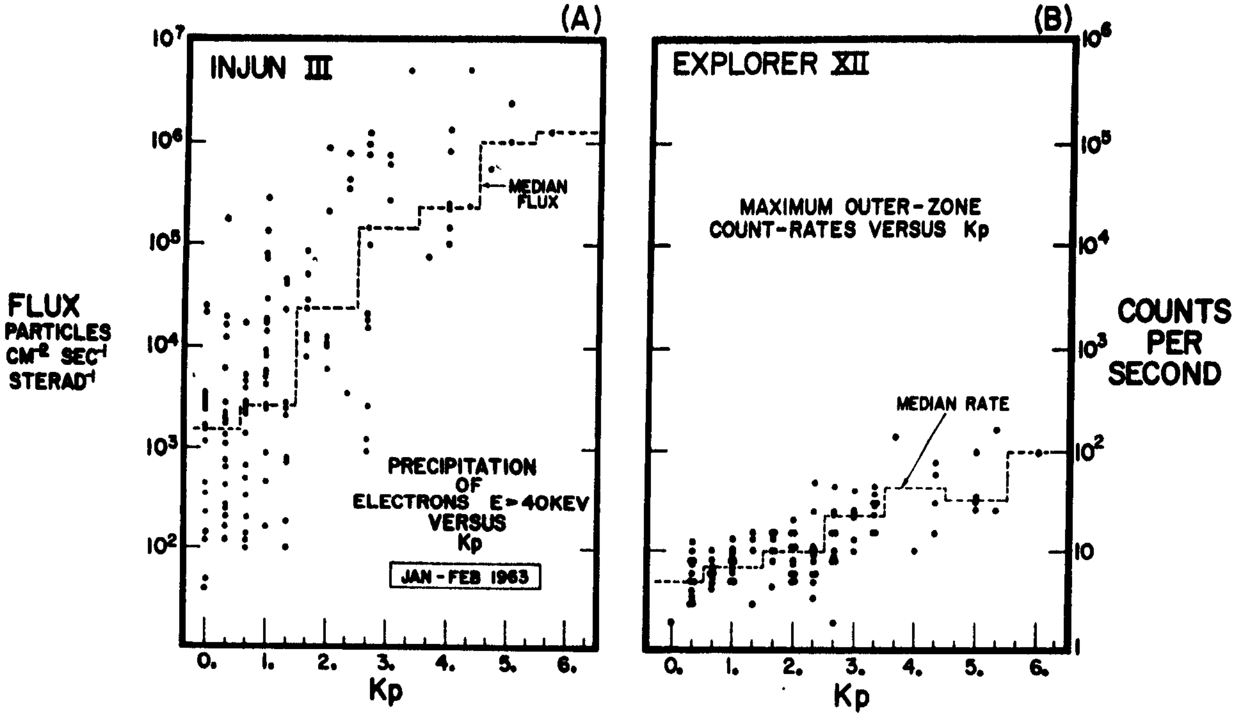

Figure 6 - Illustration that the flux or precipitated electrons (in A) varies more with $K_p$ than does the omnidirectional flux (mainly of trapped electrons) in the equatorial plane (in B). Each point shows the maximum respective flux encountered on an outer-zone pass. (After O'Brien, 1964)

that the precipitation has its maximum close to the poleward boundary of the region of trapped electrons, their results may be interpreted in terms of possible extension of precipitated electrons.

Maehlum and O'Brien (1963) found that during magnetic storms there was a very sharp boundary of the region where trapped electrons of energy above 40 kev could be observed. For this boundary, measured in L, they used the symbol $L_n$. It can be seen as a function of the $K_p$ index during one geomagnetic storm in Figure 7. When $K_p$ reached its maximum value of 9, $L_n$ had its minimum value of 4. Maehlum and O'Brien (1963) also found that the poleward boundary of strong radio wave absorption followed the $L_n$ quite closely during the storm.

The effect of $K_p$ on $L_n$ is similar to the equatorward movement of the region of visual aurora during strong magnetic storms, which has been studied in the last few years in detail for some storms by Akasofu (1962, 1963a, b) and others.

(e) The Spectrum of Precipitated Electrons

Up to now only very rough measurements of the energy spectrum of the precipitated electrons have been reported. In most cases the proposed spectra have been obtained from two instruments with different energy characteristics. They thus are to be considered as rough equivalent spectra for measurements made in a defined way. In addition, it has been found that the equivalent spectrum is highly variable both in space and time (cf. O'Brien et al., 1962). Nonetheless the available spectral data are of great interest at the present stage of knowledge in the field, and they even make it possible to draw some interesting conclusions about ionospheric effects of the precipitated electrons. These will be discussed in the following sections.

Most spectra that have been reported hitherto can be divided in two categories if they are expressed in an exponential form. On one hand, the e-folding value, b, in the spectrum of precipitated electrons, written in the form $\alpha \exp(-E/b)$, has been found often to be in the range 2-8 kev (McIlwain, 1960; Stilwell, 1963; Sharp et al., 1964a, b, c). This is a very steep spectrum but even steeper ones have been observed. McIlwain interpreted his rocket measurements in a strong aurora as indicating a monoenergetic flux of electrons with an energy of about 6 kev. Krasovskii et al. (1962) has observed steep spectra for precipitated electrons with a most common equivalent energy value of 14 kev.

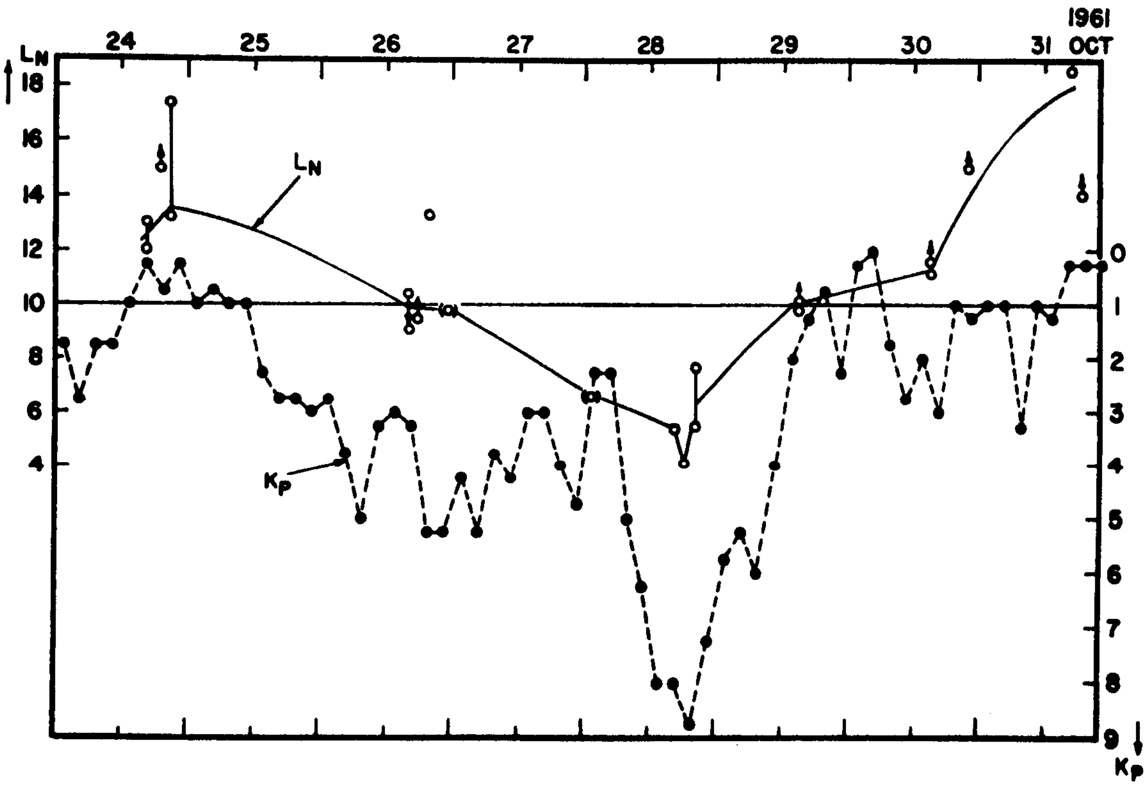

Figure 7 - Variation of the northern boundary of trapping with $K_p$ during a geomagnetic storm, as observed by Injun at a height of about 1000 km. (After Maehlum and O'Brien, 1963)

The majority of the existing measurements have been made with Geiger tubes, for which the minimum detectable electron energy is about 40 kev. These measurements have mostly given e-folding values much higher than those mentioned above, namely, between 20 and 45 kev. (Davis et al., 1960; McDiarmid et al., 1960; O'Brien et al., 1962; Mann et al., 1963; O'Brien and Taylor, 1964). Mann et al (1963) found from measurements during only some 20 orbits that the values within this range were grouped in two classes, 25 ± 5 kev and 42 ± 3 kev.

The balloon measurements of x-rays at 30-35 km altitude also, in general, give inferred spectra of incident electrons of a fairly flat type, corresponding to e-folding energies in the range 20-45 kev (cf. e.g., Anderson and Enemark, 1960), although power law spectra often are found to fit the observations somewhat better than exponential spectra.

Recently the first direct measurements of precipitated electrons below 1 kev energy have been reported (Sharp et al., 1963; Evans et al., 1964). They showed that there is generally not very much energy flux below 1 kev. In some passages through the auroral zone Sharp et al. (1964c) found the integral fluxes above 0.18 and 10 kev to correspond to equivalent exponential spectra with e-folding values between 2 and 5 kev. On other occasions they did not find any energy flux at all below 1.5 kev. That there is not very much energy flux below 1 kev is also evident from observations of the luminosity distribution with height of aurorae. O'Brien and Taylor (1964) give an example of measurement results obtained on board Injun 3, according to which less than 0.1% of the auroral light originated above the satellite, that was at 250 km altitude. From this they conclude that the number of 10 ev electrons in the precipitated flux was no larger than the number of 10 kev electrons. It therefore seems probable that the spectrum, in general, does not increase very fast below 1 kev, which means that it is not of the power law type at these low energies.

Sharp et al. (1964c) found a significantly harder spectrum on the dayside than on the nightside. This observation agrees with multi-frequency riometer measurements of auroral absorption by Lerfald et al. (1964), according to which the absorbing ionization is located lower down in the atmosphere in the day than in the night.

Of special interest are the statistical data on electron precipitation published recently. As mentioned earlier the precipitation is most intense near the auroral zone. O'Brien (1964) found an average flux of about $4.10^5$ electrons/$cm^2$ sec in the precipitation cone at an invariant latitude of 65°. Injun 1 had a CdS detector, measuring electrons of energy above about 1 kev (O'Brien, 1962b). O'Brien and Taylor (1964) state that the flux of $4.10^5$ electrons/$cm^2$ sec of energy greater than 40 kev was associated with an energy flux of 4 ergs/$cm^2$ sec for electrons of E $\gtrsim$ 1 kev. These data should be considered as accurate to a factor of about three. Using these two values an equivalent electron spectrum in the range 1-40 kev can be deduced. It is found to be

$$n(E) = 7.8 \cdot 10^7 e^{-E/5.7} \text{ electrons/cm}^2 \text{ sec kev.}$$

For the energy values 40 and 250 kev similar average fluxes have been obtained from the Alouette measurements reported by McDiarmid et al. (1963). While the flux above 40 kev had its maximum at an invariant latitude of 65°, the flux above 250 kev was maximal at about 60 degrees. McDiarmid et al. (1963) did not present any details for the latitudinal variation of this latter integral flux. By applying a rough correction factor of 0.1 for the latitude variation of the average flux above 250 kev from 60 to 65 degrees invariant latitude, the following approximate equivalent spectra for the energy range 40-250 kev can be derived for two ranges of magnetic activity in the auroral zone ($\Lambda$ = 65°), if isotropy is assumed for the upper hemisphere

$$K_p < 4: \quad n(E) = 1.2 \cdot 10^4 \; e^{-E/41} \text{ electrons/cm}^2 \text{ sec kev}$$

$$K_p > 4: \quad n(E) = 2.4 \cdot 10^5 \; e^{-E/30} \text{ electrons/cm}^2 \text{ sec kev}$$

(cf. Hultqvist, 1964b). The applied latitude correction is probably too large as judged from a comparison of the latitude distribution of passes in which the intensity of precipitated electrons with energies greater than 250 kev was greater than $3.2 \cdot 10^3/cm^2$ sec ster (Figure 8 of McDiarmid et al., 1963) and the corresponding diagram for 40 kev. The resulting spectra are thus too steep rather than too flat, and the absorption caused by electrons in the energy range 40-250 kev is probably larger than the values presented below.

As mentioned, the spectra of precipitated electrons are very variable. There is also an important latitude variation in the steepness, which increases with latitude (O'Brien et al. 1962; McDiarmid et al., 1963; O'Brien, 1964). On the other hand there seems to be no significant dependence of the spectrum on pitch angle or on the intensity of precipitation (O'Brien, 1964).

To obtain the equivalent spectra the averaging has been made over a large number of measured integral fluxes. With a variation of a factor of $10^5$ the use of averages may be questioned. It is also questionable whether average integral fluxes are the best values to use when the interest is in the average electron density produced by the particle influx. The average electron density is then defined by the averaging process employed and this method of averaging is not identical with the averaging made in measuring the ionospheric absorption, for instance. It can, however, be shown that the average electron density produced by the precipitated electrons can be expressed in the average integral fluxes measured on the satellites. Since only two experimental integral flux values are available, one has to fit a two-parameter energy relation for the average flux to these experimental data (Hultqvist, 1964b), as has been done above.

## Quantitative Relations Between Electron Precipitation and Photon Emission in Aurora

Two direct measurements of the quantitative relation between precipitation and photon emission will be discussed here, namely those of McIlwain (1960) and O'Brien and Taylor (1964). It is of interest to compare their results with what is expected on theoretical grounds.

McIlwain did not use any filter, but measured the photon flux integrated over the transmission curve of the photomultiplier. If we assume that 1/5 of the light was λ 3914Å, the measured photon flux corresponds to an emission rate of about 3 kilorayleigh at this wavelength. The fraction, 1/5, is fairly arbitrary, but it seems reasonable (cf. e.g., Dalgarno, 1964) and is probably in error by less than a factor of 2 and 1/2, respectively, for an ordinary auroral zone aurora. McIlwain's (1960) measured electron flux corresponds to an energy flux of 20 erg/cm$^2$ sec, if the spectrum obtained was extrapolated to $E = 0$. Thus, the resulting electron energy flux required per unit of λ 3914Å emission rate is 7 ergs/cm$^2$ sec per kR.

O'Brien and Taylor (1964) reported an average λ 3914Å intensity of 2(+4/-1.5) kR at the maximum of the latitude distribution, i.e., in the auroral zone. As mentioned above, the electron measurements gave a corresponding average of the flux above 40 kev of $4 \cdot 10^5$ electrons/cm$^2$ sec and an energy flux for E $>$1 kev of about 4 ergs/cm$^2$ sec, which values they consider as accurate to a factor of about three. In order to get a value directly comparable with that of McIlwain one would have to extrapolate the energy spectrum from 1 kev down to E = 0 and evaluate the total energy flux. Using the equivalent exponential spectrum, we find 5 ergs/cm$^2$ sec for E $>$ 0. Thus the Injun 3 results give 2.5 ergs/cm$^2$ sec per kR. Considering the uncertainties in measurements and the method of evaluation, this is a good agreement.

What energy flux per kR does one expect on the basis of existing knowledge about the emission processes? Omholt (1957, 1959), Chamberlain (1961), Rees (1963), and Dalgarno (1964), among others, have discussed this. It has been shown by Stewart (1956) that the ratio between the excitation cross section for the 3914Å band of $N_2^+$ and the total ionization cross section is constant, at least up to 200 ev energy, and has the value 0.02. Assuming that this value is true over the whole energy range of interest, one finds that 50 electron-ion pairs are produced for each 3914Å photon. Since the mean energy expended by fast electrons in nitrogen per electron-ion pair is 35 ev (at least for energies down to a few hundred ev; it is assumed that the figure is correct down to zero energy), we find that 50 x 35 = 1750 ev is dissipated per 3914Å photon. Since each photon has an energy of 3.2 ev the efficiency with which energy is converted into 3914Å radiation is $1.8 \cdot 10^{-3}$. When the initial energies of the fast electrons fall below perhaps 100 ev, these efficiencies must decrease sharply (Dalgarno and Griffing, 1958; Dalgarno, 1964). One kR of 3914Å photons corresponds to an energy influx of 2.8 ergs/cm$^2$ sec, if the efficiency figure $1.8 \cdot 10^{-3}$ is employed. Dalgarno (1964) has used the value $1 \cdot 10^{-3}$. With this conversion efficiency we find the energy flux requirement to be 5.1 ergs/cm$^{-2}$ sec$^{-1}$ per kR. The agreement between these values and the experimental ones of McIlwain (1960) and O'Brien and Taylor (1964) is better than expected, when the uncertainties in the analyses are taken into account.

The total efficiency of converting particle energy into photons of any energy is expected to be about 1% on theoretical basis (cf. Chamberlain, 1961). McIlwain found from his rocket measurements a value of only 0.2% while preliminary Injun 3 results point towards 1% (O'Brien and Taylor, 1964).

## Auroral Absorption

Auroral absorption is in general defined on riometer records as all the absorption, generally irregularly varying, which is usually observed during magnetically disturbed conditions and which is not associated with either polar cap absorption (PCA), produced by high energy solar protons, or sudden cosmic noise absorption (SCNA), which is caused by solar ultraviolet radiation. The auroral absorption is thus defined as the remainder when one has excluded two well defined types of absorption. It is therefore not surprising that it recently has been found to contain a number of phenomena differing, for example, in the energy characteristics of the ionizing agent (Ansari, 1963). The name may, however, be motivated by the fact that there is a fairly good correlation between auroral absorption and the general level of magnetic disturbance (cf. e.g., the review by Hultqvist, 1963c).

It has long been known that some of the auroral absorption is located below the E-layer, i.e. in or below the D-layer. Such evidence arises, for instance, from ionosondes, which frequently are blacked out during magnetic storms. This shows that all the radio energy is absorbed between the earth's surface and the E-layer. It has not been clear, however, whether all the absorption, for sufficiently high frequency cosmic noise, takes place below the E-layer or whether there may be as much or even more absorption at E-layer heights. In fact, there are reasons to believe that the absorption produced by those electrons which are the cause of the visible aurora should be located mainly up in the altitude range where the aurora occurs. Evidence has recently been presented against the hypothesis of Chapman and Little (1957) that the main part of the radiowave absorption is produced below 90 km by x-rays from the primary auroral electrons. The absorption due to primary electrons of an energy spectrum as measured in visual aurora by McIlwain (1960), is probably at least an order of magnitude greater than that due to the bremsstrahlung x-rays the electrons give rise to (Ansari, 1963; Hultqvist, 1963, 1964; Brown, 1964).

The height of the main part of the auroral absorption became an important parameter for the understanding of the electron reactions in the lower ionosphere when it was found that there is a much smaller influence of the sunlight on the absorption value than was expected on the basis of existing models (cf. e.g., the review by Hultqvist, 1963c). A very small sunlight effect would be expected if all auroral absorption took place up in the height interval of the ordinary visible aurora. But such a height distribution would be in conflict with a large body of other experimental observations (cf. e.g., Hultqvist, 1963a, b, c). It would appear that the satellite measurements reported by Mann et al. (1963), McDiarmid et al. (1963), O'Brien (1964) and O'Brien and Taylor (1964) give a solution of this problem.

An important satellite observation in this respect is that of Mann et al. (1963) that there occurs frequently beside the soft type of spectrum of the precipitated electrons, observed in visible aurora by McIlwain (1960), a harder type with the e-folding energy between 25 and 45 kev. The averages of the extensive statistical satellite data of McDiarmid et al. (1963) and O'Brien (1962b, 1964) correspond to equivalent spectra given on page 11. Thus the e-folding energy is about McIlwain's value for the low energy range and is appreciably higher in the higher range.

Having these average spectra it is possible to calculate how much absorption is produced by the electrons below and above 40 kev energy. This has been done by Hultqvist (1964a, b). Figure 8 shows the height distribution of absorption per km due to the following spectra (Hultqvist, 1964a)

Curves No. 1: $5 \cdot 10^9 \, e^{-E/5}$ electrons/cm$^2$ sec ster kev corresponding to a very strong visual aurora of international brightness coefficient between III and IV;

Curves No. 2: Due to the bremsstrahlung x-rays produced by the electrons giving rise to curve No. 1;

Curves No. 3: $7 \cdot 10^4 \, e^{-E/41}$ electrons/cm$^2$ sec ster kev which was observed over the auroral zone by Mann et al. (1963).

It can be seen from Figure 8 that although curve No. 1 corresponds to a very strong aurora, the riometer absorption due to the hard electron spectrum (curve 3), which has its peak as low as 70 km altitude, is larger. The total absorption for daytime was found to be 0.9 db for the soft electron spectrum and 1.9 db for the hard one. Even if the uncertainty in the computed absolute absorption values is fairly high (cf. Hultqvist, 1964a) it is probably less than a factor of three for the relative values due to the various spectra.

The profiles shown in Figure 8 can, with proper absorption scale, be used for estimating the absorption caused by the average precipitation spectra observed by the Injun and Alouette satellites. The e-folding value in the range 1-40 kev was found to be 5.7 kev (see page 11). This

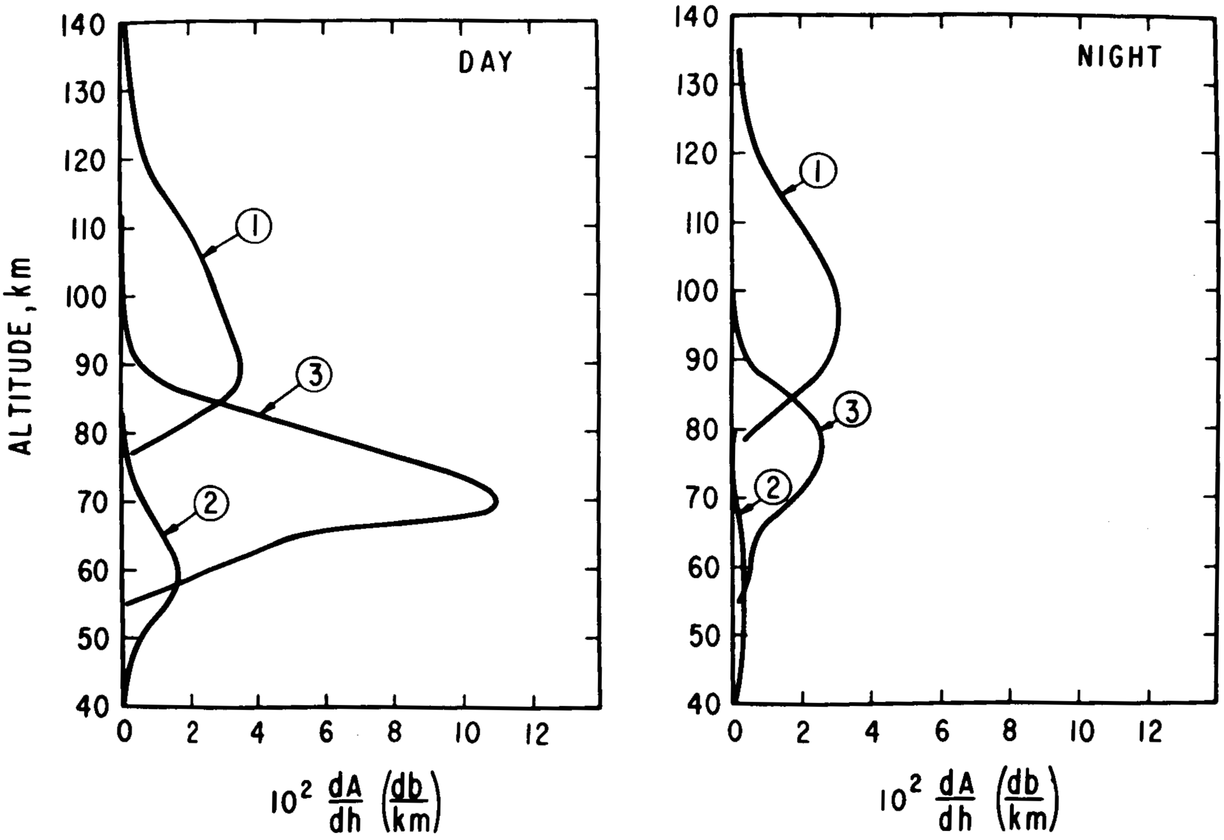

Figure 8 - (a) is for daytime and (b) for night. Curves 1 in (a) and (b) show the height distribution of the absorption produced by the differential energy spectrum $N(E) = 5.10^9 e^{-E/5}$ kev electrons $cm^{-2}$ $sec^{-1}$ $ster^{-1}$ $kev^{-1}$. The total absorption values corresponding to curves 1 amount to 1.04 db in the day and to 0.89 db at night. Curves 2 give the absorption due to the bremsstrahlung of the same electron spectrum. Total absorption in the day is 0.27 db and in the night 0.061 db. Curves 3, finally, represent the absorption distribution produced by the differential energy spectrum N(E) $7.10^4 e^{-E/41}$ kev electrons $cm^{-2}$ $sec^{-1}$ $kev^{-1}$, coming in along the field lines. Total daytime absorption under curves 3 is 1.9 db. The nighttime one is 0.52 db, if the height profiles of the ratio of negative ion to electron density used by Nicolet and Aikin (1960) and others are employed.

is very close to McIlwain's (1960) value 5.0 kev. In fact, the spectrum $2.4 \cdot 10^8 e^{-E/5}$ electrons/cm$^2$ sec kev contains the same number of electrons above 40 kev as the average observed by Injun 3 ($4 \cdot 10^5$ electrons/cm$^2$ sec; O'Brien and Taylor, 1964). It corresponds to a total energy flux above 1 kev about twice as high as the average value (4 ergs/cm$^2$ sec) given by O'Brien and Taylor (1964). However, the corresponding energy flux per kilorayleigh is about 5 erg/cm$^2$ sec which is equal to the average of the values found by McIlwain (1960) and O'Brien and Taylor (1964).

Using the equivalent spectrum $2.4 \cdot 10^8 e^{-E/5}$ electrons/cm$^2$ sec kev for the 1-40 kev range and the $1.2 \cdot 10^4 e^{-E/41}$ electrons/cm$^2$ sec kev for 40-250 kev during low magnetic activity ($K_p < 4$), the electron density profiles 3 and 1 in Figure 9 are found. The total absorption produced by these two spectra are 0.09 db and 0.32 db, respectively.

For $K_p > 4$ the average fluxes of McDiarmid et al. (1963) above 40 and 250 kev correspond to the exponential spectrum $2.5 \cdot 10^5 e^{-E/30}$ electrons/cm$^2$ sec kev. For this spectrum only an upper limit of the electron density and absorption can be obtained with the use of Figure 8. Curve 2 in Figure 9 shows this upper limit for the electron density. The corresponding upper limit of the total absorption is 1.4 db. Lower limits for the average electron density distribution and absorption are the values given for $K_p < 4$, i.e., curve 1 in Figure 9 and the corresponding absorption value of 0.32 db. The total riometer absorption due to the average electron spectrum in the energy range 40-250 kev is thus found to be about 1 db during the moderately disturbed conditions for which the observations are representative.

Two assumptions were made in the computations described above, which both tend to increase the relative importance of the absorption caused by precipitated electrons in the range 1-40 kev. One is that the equivalent average spectrum for the energy range 40-250 kev is probably less steep than the spectra used in the calculations. The other is that the equilibrium relation between electron density and the ionization rate was used. The computed absorption is therefore certainly overestimated. Since the effective recombination coefficient decreases from 60 km upwards the overestimation will be most important at greater heights. It does not seem probable that the error in the average absorption per unit height in the lowermost part due to unequilibrium would exceed a factor of two, since the rate of variation of the electron content, as seen on riometer records, mostly is slow compared with the recombination time in that part of the ionosphere. It is thus probable that the relative contribution of the absorption caused

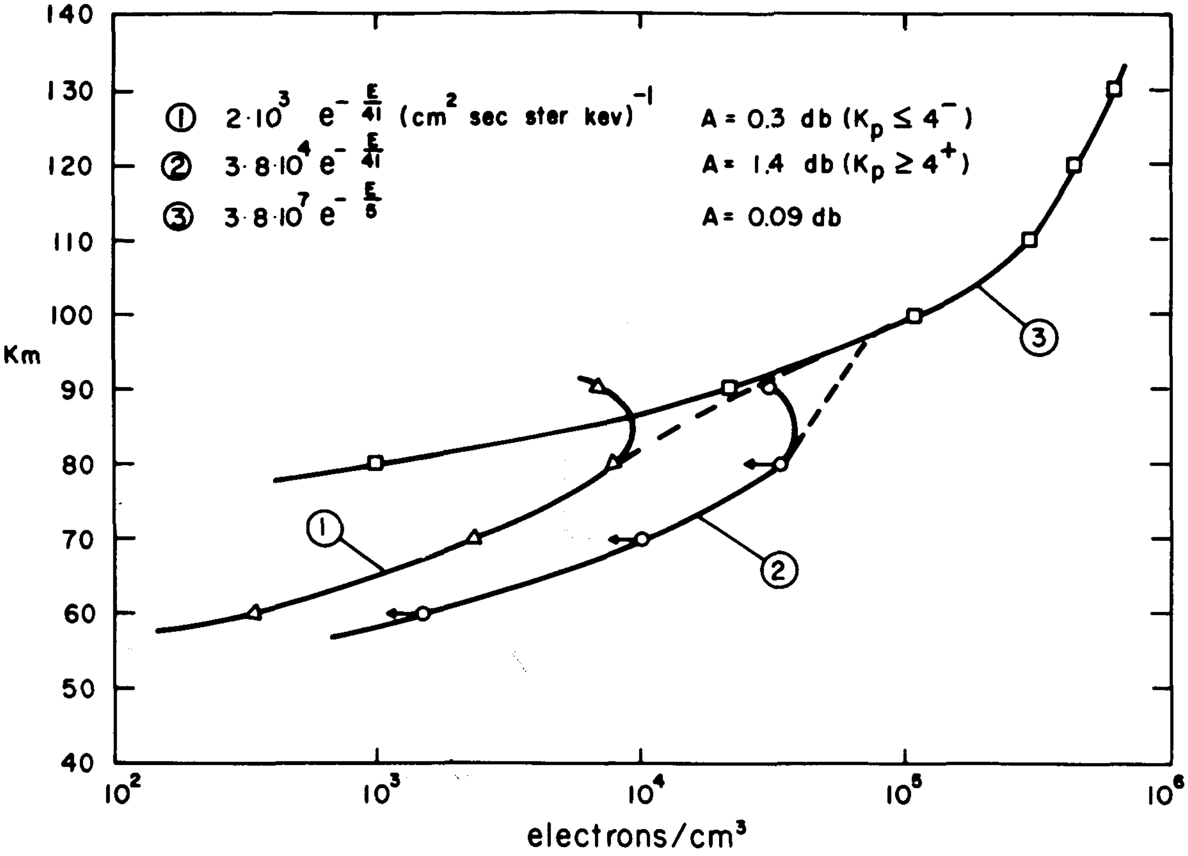

Figure 9 - Electron density profiles due to three different energy spectra of precipitated electrons. The spectra as well as the total absorption, A, at 27.6 are given in the figure. Curve No. 2 gives an upper limit for the equilibrium electron density distribution produced by the spectrum $3.8.10^4 e^{-E/30}$ $(\mathrm{cm}^2$ sec ster kev$)^{-1}$. A lower limit for this spectrum is curve No. 1.

by the low energy electrons (corresponding to curve no. 3 in Figure 9) is smaller than shown by the figures given above.

Since the average absorption values produced by "soft" and "hard" electrons differ by an order of magnitude at least in the day, it seems possible to draw some conclusions on their basis.

Most of what is called auroral absorption seems to take place below 90 km. Hence the reason for the observed very small influence of sunlight on the intensity of the absorption is <u>not</u> that the absorption is located mostly above 90 km altitude, (where, according to virtually all models that have been proposed in the last few years, the density of negative ions is negligible in both day and night). One apparent interpretation of this observation is that the negative ions in fact are negligible, even in the night, down to about 60 km (as proposed by Hultqvist, 1962, 1963a, b). In any case it seems that the electron chemistry in the lowest ionosphere is quite different from what has hitherto been believed.

The virtual absence of sunlight influence on auroral absorption taking place mainly in the range 60-90 km thus leads to the conclusion that photo detachment is not important in that height interval. If this is true, the problem cannot be solved by assuming that the detachment of electrons from negative ions, in the height range mentioned, requires ultraviolet radiation, as proposed and discussed by Eriksen et al. (1960) and Reid and Leinbach (1962), and Reid (1961).

The result that the auroral absorption is produced mainly by electrons of energy above 40 kev, while the visible aurora is caused by lower energy electrons (cf. e.g., McIlwain, 1960) makes the fairly poor observed correlation between visible aurora and absorption understandable. By combining low-energy and high-energy electron spectra in various proportions, one may expect to see visible aurora practically without absorption, strong absorption without visible aurora, and all combinations in between. This is what has been found in the detailed study by Ansari (1963). There is a different local time dependence of the occurrence frequency of the low and high energy parts of the precipitated electron spectra. The auroral absorption has a pronounced maximum in the auroral zone in the morning hours, whereas the visual aurora has its maximum in the middle of the night. So there seems to be some mechanism that accelerates the electrons on the average to higher energies over the morning side of the auroral zone.

The quantitative estimations of average absorption values presented above refer to the auroral zone. As has been pointed out earlier there is a tendency for the electron spectrum to grow steeper with increasing latitude and the conclusions drawn may not be true far inside the auroral zone. On the other hand the conclusion that auroral absorption is located mainly below 90 km is probably valid at subauroral latitudes. This is indicated also by the observed good correlation between bremsstrahlung x-rays and visual aurora at these latitudes (cf. e.g., the review by Winckler, 1962).

The deductions in this section are based on average fluxes and average spectra derived from widely varying, measured electron fluxes at two energies each, only. Conclusions should certainly be drawn from them with great care (cf. also page 12), but it seems that the order of magnitude results presented above should be fairly significant.

The height distribution of auroral absorption is quite similar to what has recently been found by means of multifrequency riometer measurements by Lerfald et al. (1964). The multifrequency absorption measurements can, however, provide height information only in the interval 35-75 km. A possible contribution from ionization up in the visible aurora in the presence of absorption also at lower altitudes cannot be measured by that technique, whereas the satellite measurements, reviewed above, clearly indicate that, on the average, most absorption is produced below 90 km altitude.

The total absorption values obtained from the Injun and Alouette measurements are in quite reasonable accordance with the average absorption during the five most disturbed and five most quiet days per month, as observed over several years at College (geomagnetic latitude 64.5°) by Basler (1963). For the disturbed days he found a daily average of about 1 db in the summer and between 1 and 2 db in winter and at equinoxes–as compared to about 1 db given above for $K_p > 4$. For the quiet days the daily average at College was about 0.3 db (to be compared to the value 0.3 db for $K_p < 4$ above).

Figure 3 shows the fraction of passages for which the absorption would be estimated to be greater than about 0.2 db for high and low magnetic activity.

## The Lower Ionosphere at Night

A number of hypothesis of corpuscular ionization of the ionosphere have been advanced to explain the existence of appreciable electron densities in the night and especially during the polar night (see Antonova and Ivanov-Kholodny, 1961). Mariani (1964) has invoked a corpuscular flux with a peak value of about 0.1 erg/cm$^2$ sec of electrons with energies of the order of 1 kev at geomagnetic latitudes between 55 and 65° to explain the correlation of maximum electron density in the F-region at noon with solar activity. Willmore (1964) has found evidence for a particle energy influx of the order of 20% of the UV photon flux from Ariel I measurements of temperatures in the F-region. He also found good agreement between the geographical distribution of the temperature and of particle fluxes observed by Sputnik II. Harris and Priester (1962) assume a corpuscular heat source comparable in influence to the ultraviolet solar radiation, i.e. of the order of a few ergs/cm$^2$ sec, in their model for the solar cycle variation of the upper atmosphere.

The electron density in the F-layer should decrease by a factor of 100 or more in 5-10 hours after sunset, at that altitude, if no ionization took place. As the observed decrease in general is only a factor of 10-20 in the altitude interval 120-200 km and 3-10 in the F-region, the obvious conclusion is that some nighttime ionization process exists. The need for such a process is still stronger in order to explain the fairly high electron densities observed over the central polar caps during the long polar nights. For instance, at the Pole Station (latitude 90°S) at midnight in the midwinter the foF was about 5 Mc/s in the high-solar activity year 1958 and a little above 3 Mc/s three years later. The nighttime foF was not very much less than the noon value in the summer. It is true that foF is not a good measure of the electron production rate in the upper ionosphere, especially not in the polar night, as dynamical effects within the ionosphere are very important, but even so it can definitely be said that an ionization source must exist.

Does the observed flux of precipitated electrons contain enough energy to produce the lower ionosphere at night? It is not possible to give any accurate answer to that question now, since no extensive measurements of energy fluxes below 1 erg/cm$^2$ sec have been made in the lowest part of the electron energy spectrum of interest. Another piece of missing information is the energy flux associated with low energy protons. Krasovskii et al. (1963) have observed appreciable fluxes of positive ions with energy above 200 ev at low and medium latitudes ($\leq 49°$). The ion flux was usually about $10^8$/cm$^2$ sec ster and the energy flux associated with it was probably $\leq$ 0.1 erg/cm$^2$ sec. It is not known whether the ions were trapped or precipitated. Above 100 km altitude not only precipitated electrons, as defined in the introduction, but also trapped ones contribute to the production of free electrons, and their contribution may even exceed that of the precipitated electrons. No observational results are yet available from which the energy dissipation into the atmosphere by protons can be evaluated.

It is obvious from Figure 9 that the average electron flux produces quite sufficient electron densities down in the E-layer in the auroral zone. A numerical calculation using the same spectrum as for curve 3 in Figure 9, for 200 km altitude gives an electron production rate of 1400 electrons/$cm^3$ sec, corresponding to an equilibrium electron density of from $4 \cdot 10^5$ to $2 \cdot 10^6/cm^3$, depending on the recombination coefficient used (Mitra, 1959, Van Zandt et al., 1960, or Schmerling and Grant, 1961). Therefore the corpuscular energy source is probably sufficient for production of the nighttime F-layer too in the auroral zone.

The electron densities shown in Figure 9 are astonishingly high. They correspond to critical frequencies higher than are normally observed in the auroral zones. They were derived, however, without taking dynamic effects into account and there may very well be uncertainties of a factor of four or so due to the inaccuracy in the experimental average particle fluxes, as well as in the atmospheric parameters used in the derivation. To this comes that the equilibrium relation has been used in computing the electron density from the ionization rate. Too large values of electron density and absorption is probably obtained in that way. On the other hand the ionization produced by electrons mirroring above 100 km has not been taken into account which counteracts the effect of the use of the equilibrium relation between electron density and ionization rate.

It is not known to this author whether the observed enormous variability of the precipitation fits into the time behaviour of the nighttime ionosphere.

What can be said about the ionosphere over the central polar cap in respect of observed particle energy dissipation? The average flux of precipitated electrons above 40 kev energy was found to be 10-100 times smaller than in the auroral zone at 76° invariant latitude by Injun 3 (O'Brien, 1964) and 100-1000 times smaller by Alouette (McDiarmid et al., 1963). Precipitation did not take place continuously well inside the auroral zones, but it varied in intensity from cosmic ray background to $10^5$ electrons/$cm^2$ sec ster. Spectral information for the central polar caps is not available at the time of writing. The best that can be done to obtain an idea about the electron production rate over the polar caps from earlier presented results, seems to be to assume that the spectrum is about the same as used above for the auroral zone and to reduce the ionization rate in proportion to the difference between the two regions in counting rate found by Injun 3 and/or Alouette.

The corresponding energy flux for electrons of energy above 1 kev will thus be in the range $10^{-2}$ to 1 erg/cm$^2$ sec and the steady state electron densities 1/30 to 1/3 of those for curve no. 3 in Figure 9. For a 200 km electron density of $10^6$ cm$^{-3}$ in the auroral zone a corresponding electron density range of $3 \cdot 10^4$-$3 \cdot 10^5$ electrons/cm$^3$ is obtained for the polar caps, neglecting all dynamical effects. The corresponding plasma frequency is between 1.6 and 4.9 Mc/s. These values should be compared with the foF value of about 3 Mc/s observed at the Pole Station during somewhat higher solar activities. At 100 km altitude the plasma frequency would be between half an Mc/s and one and a half Mc/s. Despite the roughness of this estimate it seems possible to state that the observed precipitation of electrons of energies above 1 kev must contribute significantly to the nighttime ionosphere over the polar caps and that one cannot rule out the possibility that it is the main source.

At subauroral latitudes the average values found from the Injun 3 data (O'Brien, 1964) by making the same assumptions as for the polar caps are the following:

energy flux: $10^{-2} - 10^{-1}$ erg/cm$^2$ sec,

equilibrium electron density at 200 km: $3 \cdot 10^4 - 10^5$ electrons/cm$^3$

at 120 km: $1.5 \cdot 10^4 - 4.5 \cdot 10^4$ electrons/cm$^3$

corresponding plasma frequency at 200 km: 1.6 — 2.8 Mc/s

at 120 km: 1.1 — 1.9 Mc/s.

Also in this case it seems possible to draw the same conclusion as for the polar caps: the observed precipitation of electrons of energy above 1 kev is certainly of major importance for the nighttime lower ionosphere in subauroral latitudes and it does not seem possible at the present time to exclude the possibility that it is the main source.

A problem with the precipitated-electron source of ionization is that it is highly discontinuous in space and time. It is not known to this author if the time constants of the ionospheric processes can explain that much slower variations are observed in foF, for instance.

If the electron precipitation observed by the Injun and Alouette satellites is the main source of nighttime ionization, one expects a maximum for the average nighttime electron density in the auroral zone. It seems not to be clear if such a maximum exists or not. The situation is complicated by the frequent strong disturbances there, which tend to hide an average effect.

The average absorption at riometer frequencies corresponding to the given electron densities for polar cap and subauroral latitudes is below the lower measurable limit.

The electron density produced in and below the D-layer by the average precipitation fluxes described above is orders of magnitude greater than that due to the ordinary cosmic radiation (see e.g. Mohler, 1960) in the auroral zone and is probably of the same order of magnitude or is even larger than that due to cosmic rays in subauroral latitudes, if the height profile of the ratio of negative ion to electron densities of Nicolet and Aikin (1960) and others is valid.

The average energy flux of precipitated electrons observed by Injun 3 and Alouette meets the requirements of Mariani (1964) but is somewhat smaller than that deduced by Willmore and orders of magnitude smaller than that hypothesised by Antonova and Ivanov-Kholodny (1961) and Harris and Priester (1962).

## Airglow

The following questions about airglow in connection with particle precipitation are of great interest.

(1) What limits can be put on the particle energy flux in low and medium latitudes on the basis of airglow intensities?

(2) Is it possible that the observed precipitated electrons of energy above 1 kev are responsible for part of, or all airglow?

The second question has been answered with no by O'Brien (1962b) on the basis of energy considerations. The average zenith intensity of 5577Å at midlatitudes is about 250 rayleighs (Hunten et al., 1956) which requires a precipitation rate of the order of 1 erg/cm$^2$ sec. The precipitation rate observed at midlatitudes is equivalent to orders of magnitude smaller than this.

The first question has been discussed by e.g. Ivanov-Kholodny (1962), Galperin (1962), and Dalgarno (1964). The $N_2^+$ bands are produced by impact excitation. According to Roach (see Dalgarno, 1964) 60R of 3914Å emission would not occur undetected. This puts an upper limit of about 0.3 erg/cm$^2$ sec on the possible electron precipitation rate. Galperin (1962) has claimed that the observable limit can sometimes be put much lower and the corresponding limit of the energy flux has been given as $2 \cdot 10^{-2}$ erg/cm$^2$ sec by Dalgarno (1964).

The energy fluxes derived above from the satellite measurements reported by McDiarmid et al. (1963) and O'Brien (1964) amount to $10^{-2} - 10^{-1}$ erg/cm$^2$ sec in subauroral latitudes. From this it seems that the limit given by Roach is a safe one, whereas the observed energy flux sometimes may exceed the limit given by Galperin (1962).

## Relation of Precipitated Electrons to the Outer Radiation Belt

The idea about the relations between the electrons that are precipitated into the atmosphere and the trapped electrons in the radiation belts, which was prevailing one or two years ago, was roughly that the precipitated particles were dumped from the large storage of energetic trapped particles in the magnetosphere through the influence of disturbing effects caused by the solar plasma, as, for example, the magnetic disturbances. The number of trapped particles was thought to be sufficiently large to allow the precipitation rates observed to occur with only weak and perhaps independent processes of injection and acceleration required to replenish the particles in the radiation belt, the occurrence of which is necessary to be assumed in any case for understanding the existence of the trapped radiation.

This picture has been completely changed recently through the investigations by O'Brien (1962b, 1964) of the measuring results of Injun 1 and Injun 3 and also through a number of balloon studies of x-ray fluxes in the lower atmosphere (Winckler et al., 1962, Anderson, 1964).

O'Brien (1962b) estimated the lifetime of the trapped electrons in the outer radiation belt, assuming that the source was stopped but the loss mechanisms operated at the same rate as observed by Injun 1. He found that the outer zone beyond $L \sim 2$ would drain empty of electrons in a few hours. Similar average lifetimes have also been evaluated from x-ray measurements (see e.g., Winckler et al., 1962 and Anderson, 1964). Sometimes precipitation rates several orders of magnitude above the average (more than 1000 ergs/cm$^2$ sec) have been observed (Krasovskii et al., 1961, O'Brien and Laughlin, 1962, and Winckler et al., 1962). Thus Winckler et al. (1962) recorded an electron burst reaching $10^{11}$ electrons/cm$^2$ sec, a flux which would have used up the total energy of trapped particles in the field tube in half a second, but yet it persisted for about 100 seconds. Some efficient acceleration mechanism, which can reach full efficiency in a fraction of a second, seems required.

O'Brien (1964) has also shown that the flux of trapped radiation increases when precipitation takes place instead of diminishing, which would be expected if the trapped particles were simply dumped into the atmosphere. An acceleration mechanism seems to influence precipitated and trapped particles simultaneously.

Finally, O'Brien (1964) has demonstrated that the precipitation is highly energy dependent. There was no significant precipitation or change in the flux of trapped electrons of energy greater than 1.5 Mev observed in the middle of a strong burst of electrons of energy above 40 kev. This demonstrates that the precipitation could not be due simply to a lowering of the mirror point through a decrease in the geomagnetic field, since such a mechanism would be active over the whole spectrum.

Taken together, this new evidence clearly demonstrates that the precipitated electrons which produce aurora and ionospheric ionization are not produced by dumping trapped electrons into the atmosphere. An acceleration mechanism must be involved. This mechanism must be one that can act with full strength very quickly (in a fraction of a second) and it should not change the flux of Mev electrons more than 10%, when the simultaneous changes for trapped electrons of energy above 40 kev is a hundred-fold and for the precipitated electrons above 40 kev is more than three orders of magnitude. O'Brien (1964) mentioned acceleration in an electrostatic field directed along the magnetic field lines and involving a voltage drop of the order of 10 kilovolts as one possible mechanism from the precipitation-observation point of view.

The development in the last one or two years has thus in some respects brought the model of the auroral mechanism back into the situation that existed before the discovery of the Van Allen belts. These belts have been demonstrated to be probably an effect of the same acceleration mechanism that precipitates particles into the atmosphere and produces aurora, but not the source of these particles. The "leaky bucket" model has been replaced by the "splash catcher" model, in the vocabulary of O'Brien.

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# FIGURE CAPTIONS

Figure 1 – Data from a northbound pass of Injun 3 over North America, which shows simultaneous detection of an aurora, of the precipitated electrons (with pitch angle 50°) partially responsible for causing it, and of trapped electrons. Note the approach to isotropy of the particle flux over the aurora. No attempt has been made to subtract the low-latitude contamination of the photometer signal, part of which was the detection of Cleveland, Ohio, and its surroundings. (After O'Brien and Taylor, 1964)

Figure 2 – Samples of precipitated fluxes over North America in January 1963. Each point is an 8-sec average of thirty two measurements made at half-integral values of L. The solid line gives the average flux. (After O'Brien, 1964)

Figure 3 – Percentage of passes in which the intensity of precipitated electrons with energies greater than 40 kev was greater than $1.5 \times 10^4$ $cm^{-2}$ $sec^{-1}$ $sterad^{-1}$ corresponding to 0.2 db of 30 Mc/s absorption, plotted against invariant latitude. (After McDiarmid et al., 1963)

Figure 4 – Comparison of the latitude, or L profile, of precipitation for two successive passes at about the same local time. Arrows illustrate range of fluctuation of intensities at given locations. (After O'Brien, 1964)

Figure 5 – Intensity of 3914Å auroral light averaged over 4 sec at half-integral values of L in about fifty passes of Injun 3 early in 1963. (After O'Brien and Taylor, 1964)

Figure 6 – Illustration that the flux of precipitated electrons (in A) varies more with $K_p$ than does the omnidirectional flux (mainly of trapped electrons) in the equatorial plane (in B). Each point shows the maximum respective flux encountered on an outer-zone pass. (After O'Brien, 1964)

Figure 7 – Variation of the northern boundary of trapping with $K_p$ during a geomagnetic storm, as observed by Injun 1 at a height of about 1000 km. (After Maehlum and O'Brien, 1963)

Figure 8 – (a) is for daytime and (b) for night. Curves 1 in (a) and (b) show the height distribution of the absorption produced by the differential energy spectrum $N(E) = 5.10^9 e^{-E/5 \text{ kev}}$ electrons $cm^{-2}$ $sec^{-1}$ $ster^{-1}$ $kev^{-1}$. The total absorption values corresponding to curves 1 amount to 1.04 db in the day and to 0.89 db at night. Curves 2 give the absorption due to the bremsstrahlung of the same electron spectrum. Total absorption in the day is 0.27 db and in the night 0.061 db. Curves 3, finally, represent the absorption distribution produced by the differential energy spectrum $N(E) = 7.10^4 e^{-E/41 \text{ kev}}$ electrons $cm^{-2}$ $sec^{-1}$ $kev^{-1}$, coming in along the field lines. Total daytime absorption under curves 3 is 1.9 db. The nighttime one is 0.52 db, if the height profiles of the ratio of negative ion to electron density used by Nicolet and Aikin (1960) and others are employed.

Figure 9 – Electron density profiles due to three different energy spectra of precipitated electrons. The spectra as well as the total absorption, A, at 27.6 are given in the figure. Curve No. 2 gives an upper limit for the equilibrium electron density distribution produced by the spectrum $3.8.10^4 e^{-E/30}$ $(cm^2 \text{ sec ster kev})^{-1}$. A lower limit for this spectrum is curve No. 1.