the situation in which GB is placed in a definite volume of seawater and the concentration of GB is uniform in that volume. If GB were introduced into a small portion of the total volume of seawater, the GB concentration–time profile (needed to assess the potential hazard) would be greatly influenced by diffusional and current velocities.

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28 August 1970

Auroral-Particle Precipitation and Trapping Caused by Electrostatic Double Layers in the Ionosphere

Abstract. *Interpretation of high-resolution angular distribution measurements of the primary auroral electron flux detected by a rocket probe launched into a visible aurora from Fort Churchill in the fall of 1966 leads to the following conclusions. The auroral electron flux is nearly monoenergetic and has a quasi-trapped as well as a precipitating component. The quasi-trapped flux appears to be limited to a region defined by magnetic-mirror points and multiple electrostatic double layers in the ionosphere. The electrostatic field of the double-layer distribution enhances the aurora by lowering the magnetic-mirror points and supplying energy to the primary auroral electrons.*

It was suggested by Alfvén as long ago as 1958 (*1*) that auroral particles could be accelerated by double-layer electrostatic fields that had components parallel to the earth's magnetic lines of force. He hypothesized that these fields arise from charge separation in the upper ionosphere caused by the connection by electric currents of plasma regions of different density and temperature. He also suggested that such parallel electrostatic fields play an important role in the generation of aurorae. His hypothesis is supported by the data summarized in this report, which were obtained in 1966 auroral-sounding experiments.

The existence of field-aligned electric currents was postulated by Birkeland in 1908 (*2*) and has since been observed in the ionosphere (*3*) as well as in artificially produced laboratory plasmas (*4*). Many theoretical interpretations of the experimental data have been advanced (*5*). It has been postulated (*6*) that parallel electric fields similar to the fields involved in solar flare theory (*7*) may be responsible for auroral-particle acceleration.

The evidence presented here indicates that parallel components of electrostatic fields (electrostatic double layers) do exist in the earth's ionosphere and that such double layers played a role in the production of a visible aurora observed during the fall of 1966. Data obtained from a rocket experiment suggest that the following physical processes occur in visible aurorae:

1) Mirror points of auroral-zone electrons are lowered by the presence of electrostatic double layers in the ionosphere thereby causing additional electron precipitation and contributing to the subsequent formation of a visible aurora.

2) Precipitating electrons are scattered by the atmosphere, which creates transient populations of electrons trapped between their magnetic-mirror points and the region of ionospheric electrostatic double layers.

The present experiment is not sufficiently definitive to determine how much of the approximately 10-kev electron energy (above a lower limit of 5 percent) was supplied by the parallel electrostatic field. However, it strongly suggests that electrostatic double layers contributed to the generation of a visible aurora by causing electron mirror points to be lowered into the atmosphere. We cannot rule out the possibility that a significant contribution to the electron energy was supplied by a process of longitudinal drift through a perpendicular electric field component (*8*) or that an acceleration mechanism in the neutral sheet exists (*9*).

The electron energy spectra that were measured by this experiment during a Nike-Tomahawk rocket flight launched from Fort Churchill on 16 September 1966 have been discussed previously (*10*). The inherent high angular resolution ($\approx 1/2°$) of the measurements was fully utilized in obtaining the present results.

Figure 1 shows the angular distributions obtained for the first five electron data sets. Rocket apogee ($\sim$250 km) occurred between the third and fourth electron data set. Of special interest is the deep trough at about 80°. This feature disappears at an altitude of about 200 km during the downleg of the rocket flight. (The large dip in the angular distribution that occurred near 90° is an instrumental effect caused by the shadow of the rocket. However, close observation of the orientation of the rocket spin axis throughout the flight precludes ascribing any other observed structure in the angular distribution data to shadowing effects.)

The trough observed at 80° appears to represent the dividing line between precipitating electron flux at smaller angles and a transient population of electrons trapped at larger angles extending up to 90°. Straightforward calculations indicate that the flux observed at less than 80° precipitates into the atmosphere, whereas the flux observed at larger angles mirrors at an altitude that is high enough to survive several reflections with moderate atmospheric scattering. The rapid falloff of electron flux that occurs near 100° is a result of atmospheric scattering losses.

Arguments for the above interpretation of the data are more clearly presented with the aid of Fig. 2 and a few mathematical relations derived below. Let us first consider the precipitating electrons. Assume that electrons of energy E_1 are spiraling along a magnetic line of force of strength B_1 at a pitch angle of α_1, when an electrostatic double layer with an accelerating voltage V_L in the direction of the magnetic field is encountered. We assume that the magnetic moment of the electron μ is not affected by the presence of the electric field. We then obtain the following relations, where α_0 and E_0 refer to the pitch angle and energy of the electron when these quantities are observed by the detector at some altitude (with field strength B_0) below the double layer:

$$\mu = E_\perp / B = \text{constant}$$

$$\frac{E_1 \sin^2 \alpha_1}{B_1} = \frac{E_0 \sin^2 \alpha_0}{B_0}$$

$$E_0 = E_1 + V_L$$

Thus

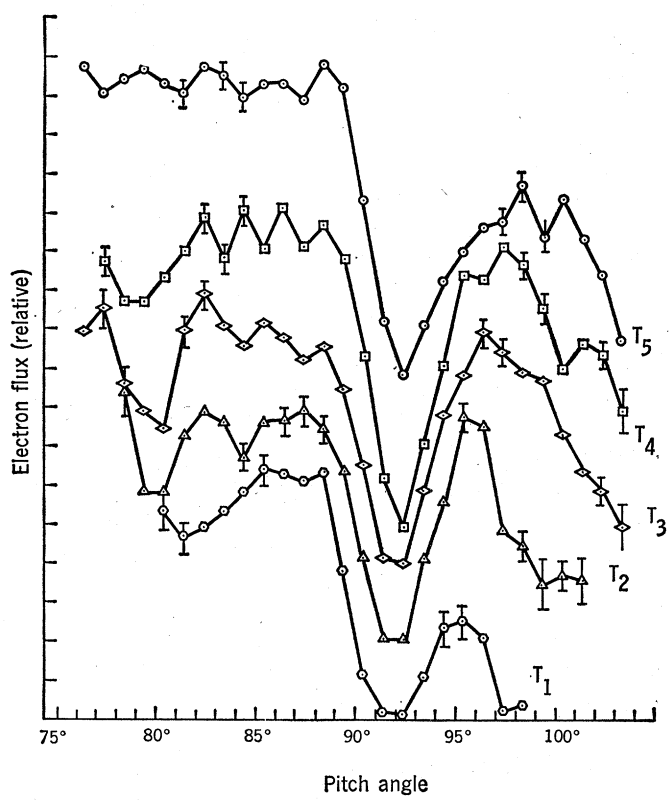
$$\sin^2 \alpha_0 = \frac{B_0}{B_1} (1 - V_L/E_0) \sin^2 \alpha_1 \quad (1)$$

If $\alpha_1 = \pi/2$, then there is a region where α_0 is less than $\pi/2$ according to Eq. 1. Therefore, the electrostatic double layer will create a region in the pitch-angle distribution between α_0 and $\pi/2$ (see Fig. 2) which is devoid of injected particles. The maximum value of pitch angle is observed when $\alpha_1 = \pi/2$ and is given by

$$\sin^2 \alpha_0 = \frac{B_0}{B_1} (1 - V_L/E_0) \quad (2)$$

Since $\alpha_0 < \alpha_1$, the mirror point is lowered and precipitation of auroral particles into the atmosphere at low altitudes may occur (see Fig. 2).

Evidence for the presence of several electrostatic double layers at low altitudes ($\approx$300 km, corresponding to $1.00 \leqslant B_0/B_1 \leqslant 1.05$) during this observation will be presented at the conclusion of this report. There is no experimental evidence that other double



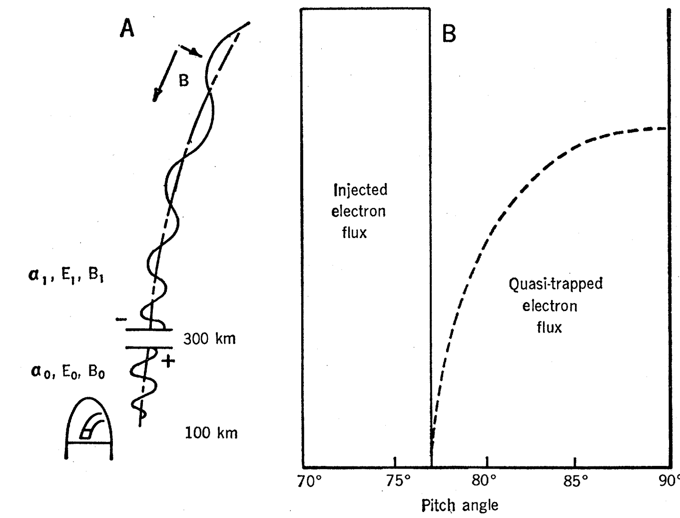


Fig. 1 (top left). Electron pitch-angle distributions measured at various times during the rocket flight. The symbols T_1, T_2, T_3, T_4, and T_5 refer to observations at altitudes of 180, 220, and 240 km during the upleg portion of the flight, and at altitudes of 240 and 220 km during the downleg of the flight, respectively. Each point represents data integrated over a 4-kev interval at the peak of the spectrum.

Fig. 2 (top right). (A) Pictorial representation of the effect of a double layer on electrons that normally mirror at about 300 km. After penetration of the double layer, the mirror points of these electrons are lowered to about 100 km, causing injection of these electrons into the atmosphere. This results in (i) quasi-trapping due to atmospheric scattering and (ii) precipitation to produce a visible aurora. (B) An originally isotropic distribution of electrons is incident on an electrostatic double layer. The effect of the parallel electrostatic field of the double layer on the pitch-angle distribution is illustrated in this figure. A void region is produced between α_0 (defined by Eq. 2) and 90° in the angular distribution. These electrons become quasi-trapped between the double layer and their magnetic-mirror points, which gives rise to the dashed line distribution shown in this figure. This results in a trough centered at α_0 and the mechanism can be used to explain the experimentally observed troughs in the data of Figs. 1 and 3.

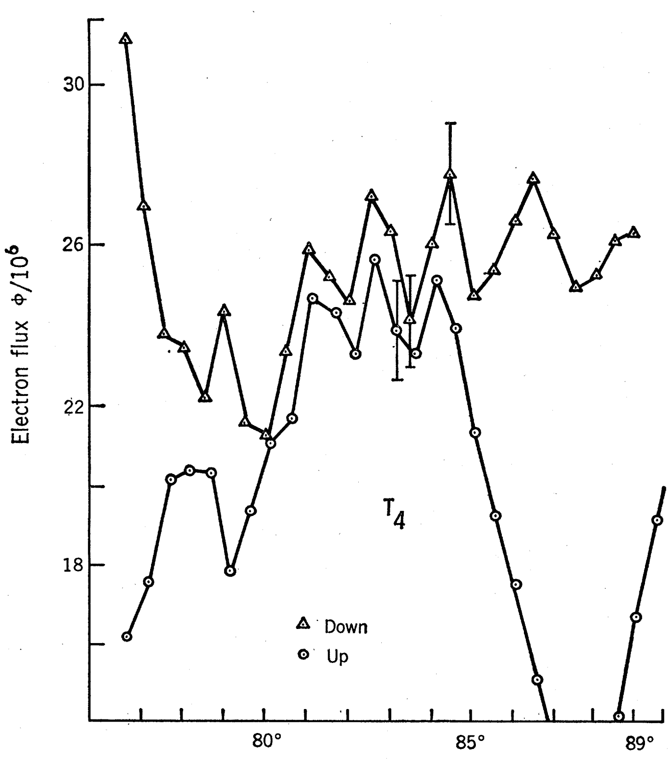


Fig. 3 (bottom left). Electron pitch-angle distribution measured at 240 km during the rocket flight. Triangular points refer to downflux data and circular points refer to upflux data. The data are similar to those indicated by T_4 in Fig. 1, but they are plotted with higher angular resolution and are integrated over a smaller energy interval (3 kev). Units of electron flux are (cm^2 sr kev sec)$^{-1}$.

layers are present at higher altitudes. However, the data do not preclude this possibility, and the higher altitude case will be considered below.

If we assume that $\alpha_0 = 77°$ (at the edge of the trough in Fig. 1) and that $1.00 \leqslant B_0/B_1 \leqslant 1.05$ and $\alpha_1 = 90°$, we obtain a limiting relationship for the double-layer total voltage and the incident electron energy, which is given by $E_1/20 \leqslant V_1 \leqslant E_1/10$. Since the incident electron energy is about 10 kev, this calculation gives a potential difference of 500 to 1000 volts across the double layers. Although a low-altitude double layer would have little effect on electron energies, it can lower electron mirror points as much as 140 to 240 km (which is well into the atmosphere). It seems clear that relatively weak electrostatic layers located at low altitudes can play an important role in the production of visible aurorae.

How do particles acquire their energy prior to their injection into the electrostatic field? The process we have just described leaves this question open. The fact that the electron spectra are nearly monoenergetic is a strong indication that the primary process for energizing the electrons involves electrostatic fields rather than stochastic processes.

The possibility exists that most of the particle energization was due to strong electrostatic double-layer fields or an electrostatic field distributed along magnetic lines of force at altitudes *far above* the observation point. Assume that particles incident at the electrostatic double layer are near their mirror point. Then,

$$\sin^2 \alpha_1 = 1$$

and from Eq. 2

$$\sin^2 \alpha_0 = (B_0/B_1) \left[E_1/(E_1 + V_L) \right]$$

At the injection edge $\alpha_0 = 77°$. Since $\sin^2 \alpha_0 \simeq 1$, we have

$$B_1/B_0 \simeq E_1/(E_1 + V_L) \qquad (3)$$

From Eq. 3 we see that by placing the double layers at an altitude of about one earth radius, $B_0/B_1 \simeq 10$, they can produce about 90 percent of the electron energy (≈ 9 kev). The same result can be obtained by a distributed parallel electrostatic field with a strength of about 2 mv/m.

To bring out more of the detail in the angular distributions, the data of Fig. 3 were plotted against smaller angular increments than were the data in Fig. 1. The data are shown as though their customary plot had been folded about an axis through 90° in order to juxtapose the downflux and upflux for studying the correspondence in their structures. The existence of the observed correlation between the peaks and troughs indicates that the structure is real. Figure 3 was obtained by superimposing data obtained from six energy sweeps (0 to 70 kev) that extended over a period of 18 seconds and included a large number (≈ 70) of rocket rotations. The correlation of the magnitudes of the peaks in the downflux and the upflux is not always so good as in Fig. 3, but the correlation of positions of peaks for all data sets is quite good.

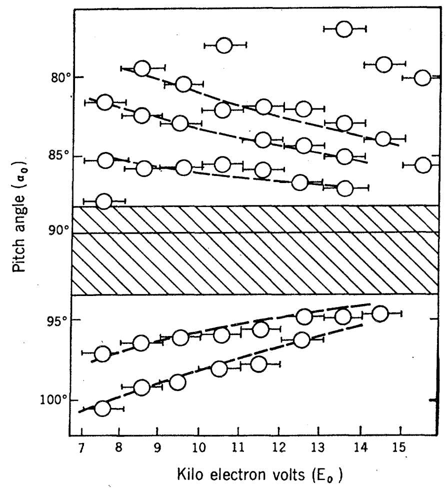


Fig. 4. Plot of the variation of the peaks in the pitch-angle distribution of Fig. 3 with energy. The dotted curve is the theoretical fit to these data (see text). The cross-hatched area corresponds to the shadow of the rocket.

It is of interest to speculate about the origin of the peaks in these angular distributions. The structure can be explained by a static picture, in which the multiple double layers do not vary in position or intensity, or by a dynamic picture, in which the double layers move along field lines or vary in intensity, or by both. We shall consider the dynamic situation first.

We believe that a localized source of trapped auroral-particle flux S with units (cm^2 sr kev sec)$^{-1}$ is produced by low-altitude atmospheric scattering. The localized trapping would not occur except for the presence of electrostatic double layers and is caused by the following mechanism: Energetic particles that would normally precipitate and be lost in the atmosphere suffer atmospheric collisions that change their direction of motion with respect to the earth's magnetic field. If their pitch angles increase, they may scatter into the forbidden pitch-angle region defined by Eq. 2, and they will then be trapped between their magnetic-mirror points and one of the electrostatic double layers.

In a given interval of energy and element of solid angle, the total number of trapped electrons per unit area N (cm^2 sr kev)$^{-1}$ is given by

$$N = SL$$

where L is the trapping lifetime when losses caused by atmospheric scattering are taken into account.

The density of trapped electrons, n, is given by the usual definition: $n = N/l$, where l is the total path length between two bounces. The trapped flux is determined by the well-known formula $\phi = nv$, where v is the electron velocity. We then obtain

$$\phi = nv = nl/\tau = N/\tau \qquad (4)$$

where τ is the bounce period.

Equation 4 shows that the flux is inversely proportional to the bounce time between trapping boundaries. The trapping boundary for a group of electrons within a given range of pitch angles may transfer between one double layer and another, owing to variations in intensity or altitude of the double layers. This transfer action causes a change in τ, and thus a change in the flux, and gives rise to either a peak or a trough in the angular distribution.

Any peak in the pitch-angle distribution caused by the double-layer perturbation would decay with a lifetime of about 1 second because of atmospheric attenuation. This effect is counteracted, however, by an increase in the flux from electron injection by the scattering source. To account for the structure observed by the present experiment, it would have been necessary for the double-layer perturbation to persist over a period of several seconds.

In the static case, structure in pitch angle may be ascribed to a different mechanism. Consider the following relationships.

From Eqs. 3 and 4 we have

$$\phi = SL/\tau \qquad (5)$$

The lifetime L (for a differential electron-energy loss) is given by

$$L = R\tau/\bar{p} \qquad (6)$$

where R is the electron range in grams per square centimeter for a differential electron-energy loss and $\bar{\rho}$ in grams per square centimeter is the atmospheric density integrated over one bounce path. We vary the path of integration by transforming the element of path length ds to the field-line component dy.

$$\bar{\rho} = 2 \int \rho \, ds = 2 \int_{Y_m}^{Y_1} \frac{\rho \, dy}{\cos \alpha} \qquad (7)$$

Y_m and Y_1 are the magnetic-mirror point and double-layer field-line coordinates, respectively. In a region where there are no electrostatic double layers, we obtain from Eq. 1

$$\sin^2 \alpha = B/B_m$$

where B_m is the magnetic field at the mirror point.

Referring the field-line coordinates B and y to the mirror point and assuming that the gradient of the magnetic field component along lines of force is constant for small displacements, we obtain

$$B - B_m = - K^{-1} (y - y_m) \, B_m$$

if $(y - y_m \ll K)$. Substituting for dy in Eq. 7 and neglecting density within the double layers, we obtain for a particle reflecting between the jth double layer and its magnetic-mirror point

$$\bar{\rho} = 4K \left[\int_{\pi/2}^{\alpha_1 L} \rho\,(\alpha) \sin \alpha \, d\alpha + \sum_{i=2}^{j} \int_{\alpha_i L - 1}^{\alpha_i L} \rho\,(\alpha) \sin \alpha \, d\alpha \right] \qquad (8)$$

where α_i^L is the pitch angle at which the electron enters the ith double layer. We may write $\rho(\alpha) = C_1 \exp (\sin^2 \alpha / C_2)$ on the assumption that atmospheric density varies exponentially with altitude.

It is clear from Eq. 8 that the largest density contribution occurs at pitch angles near $\pi/2$ because of the $\sin \alpha$ and $\rho(\alpha)$ dependence within the integral. Thus, the lifetime L, given by Eq. 6, will be substantially affected at pitch angles near 90°, which occurs when electrons have only enough "parallel" energy to barely penetrate a double layer. Rough calculations of $\bar{\rho}$ for these pitch angles indicate that the effect is of the right order of magnitude to account for the structure observed in Fig. 3.

To test more conclusively whether the pitch-angle structure is due to multiple double-layer reflections, the variation of peak position with energy was investigated. The condition for trapping that occurs when electrons do not have enough "parallel" energy to overcome the opposing voltage of the electrostatic double layers is specified by Eq. 2.

If we differentiate and eliminate V_L, we obtain the following relation:

$$B_0/B_1 = \sin^2 \alpha_0 + E_0 \, (\partial \sin^2 \alpha_0 / \partial E_0) \quad (9)$$

By rewriting Eq. 2 we obtain

$$V_L/E_0 = 1 - (B_1/B_0) \sin^2 \alpha_0 \quad (10)$$

If we measure the slope of α_0 with respect to E_0, we can determine the ratio B_0/B_1 from Eq. 9 and, thus, the locations of the double layers. The potential differences across the double layers are then given by Eq. 10.

Figure 4 illustrates the variation of pitch-angle distribution with electron energy during one observation period. The open circles indicate pitch angles at which there are peaks in the electron flux that are statistically significant.

Fits to the experimental data indicate the presence of three double layers at altitudes of about 250, 270, and 280 km corresponding to $1.0 \leqslant B_0/B_1 \leqslant 1.05$. There is a potential difference of about 160 volts across each of the upper layers and about 80 volts across the lowest double layer. The probe may have penetrated the lowest altitude double layer.

Reflections of electrons from layers at much higher altitudes are possible, but only electrons having smaller pitch angles than those observed can penetrate through the lower layers to reach them. Electrons having the requisite smaller pitch angles are not observed in the data, since they are in the atmospheric loss cone ($<80°$) and are thus obscured by precipitating fluxes.

The above values are necessarily approximate since the data were accumulated over an 18-second period and only portions of the aggregations were collected during each 3-second energy sweep. Despite difficulty in giving exact values and positions of the double layers, the results strongly indicate that there are multiple layers of about 100 to 200 volts at altitudes of about 200 to 300 km.

A study of the change of electron spectra with pitch angle is in progress. The spectrum of trapped electrons appears considerably broader than that of precipitating electrons. The energy spectrum of the injected electrons has a half-width of about 1 kev, which broadens to a half-width of about 3 kev during the trapping process. This result is qualitatively consistent with the energy spread expected from atmospheric scattering.

It must be reiterated that the present experimental results do not conclusively indicate that auroral electrons obtain most of their energy from ionospheric electric fields. However, the present results do indicate that such electric fields play an important role in the generation of visible aurorae.

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