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PLASMA SHEET PARTICLE PRECIPITATION: A KINETIC MODEL

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Abstract—Ionospheric and plasma sheet particle densities, fluxes and bulk velocities along an auroral magnetic field line have been calculated for an ion-exosphere model. It is shown that such a collisionless model accounts for many features observed above the auroral regions. Except for very strong plasma sheet electron precipitation, no large potential difference is needed along the magnetic field lines to account for the usual proton and electron fluxes, their pitch angle distributions, and auroral field aligned currents.

INTRODUCTION

The distant plasma sheet and auroral plasma are connected by common geomagnetic field lines as shown in Fig. 1 (Vasyliunas, 1970, 1972). The number densities and energies of charged particles observed in the auroral region (Sharp *et al.*, 1969, 1971; Hoffman, 1969; Burch, 1968; Frank and Ackerson, 1971; Heikkila, 1971; Evans *et al.*, 1972; Chase, 1970) and in the plasma sheet (Bame, 1968; Frank, 1967; Vasyliunas, 1968; Hones *et al.*, 1971; Schield and Frank, 1970; De Forest and McIlwain, 1971) are very similar, and the common origin of these particles seems now to be established.

Recently, Sharber and Heikkila (1972) suggested that the plasma sheet is filled by magnetosheath plasma (200 eV) flowing in from the dawn and dusk flanks and is energized by Fermi acceleration to the observed 1–5 keV, as a consequence of the inward convection of the tail magnetic field lines during substorms.

To precipitate these particles down into the auroral atmosphere various acceleration mechanisms have been proposed (Chamberlain, 1961). A parallel thermoelectric field has recently been suggested by Hultqvist (1971, 1972). In this double-layer model an electric potential difference of 600 V is supposed to be maintained by an electron temperature gradient along the geomagnetic field lines connecting the 'cold' auroral ionosphere and the 'hot' plasma sheet plasma. Since Coulomb collisions can be neglected, it has been argued that wave–particle interactions are strong enough to thermalize the electrons and maintain a near Maxwellian velocity distribution characterized by a temperature increasing from 10^3 °K at the lower boundary up to 10^7 °K at the top of this double layer.

Although topside current instabilities (Kindel and Kennel, 1971) and double-layers as described by Block (1972) can probably appear during very strong precipitation events, it is shown in this paper that the quiet time particle precipitation in the auroral region can be deduced from a collisionless model without any large potential difference *along* the magnetic field lines.

THE MODEL

In the energy range from 50 eV to 50 keV the velocity distribution of the plasma sheet electrons and protons can usually be approximated by an isotropic Maxwellian velocity distribution with a temperature of 10^7 °K (1 keV) for the electrons and 3–5 × 10^7 °K (3–5 keV) for the protons. The observed plasma sheet electron and proton densities ($n_{ps.e^-}$ and n_{p^+}) are nearly equal, each being 0·1–0·5 cm^{-3} (Vasyliunas, 1970).

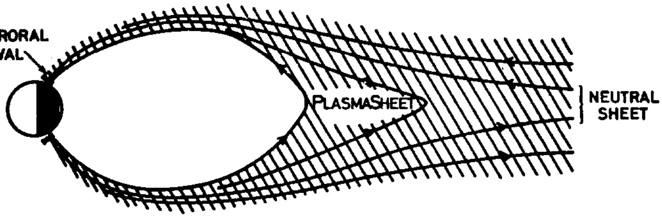

FIG. 1. CONFIGURATION OF THE PLASMA SHEET AND MAGNETIC FIELD LINES IN A MERIDIAN PLANE AT 2400 LMT (AFTER VASYLIUNAS, 1970).

In what follows we consider that these particles move through the plasma of ionospheric origin, from the equatorial source region (10–$20R_E$) down to the auroral region along the geomagnetic field lines ($\Lambda \simeq 71°$). Although the *classical Coulomb collisions* (with impact parameters smaller than one Debye length) can be neglected, it is obvious that these plasma sheet particles interact with the ionospheric plasma by *long range Coulomb collisions* (i.e. encounters with impact parameters larger than the Debye length) which are usually described by a *polarization electric field*, $\vec{E}$. This induced polarization field is calculated in our model in order to maintain (a) the local quasi-neutrality

$$n_{\mathrm{O}^+} + n_{\mathrm{H}^+} - n_{th.e^-} + n_{p^+} - n_{ps.e^-} = 0 \tag{1}$$

and (b) a zero electric current along the magnetic field lines,

$$F_{\mathrm{O}^+} + F_{\mathrm{H}^+} - F_{th.e^-} + F_{p^+} - F_{ps.e^-} = 0 \tag{2}$$

where n and F denote respectively the particle density (cm^{-3}) and flux (cm^{-2} sec^{-1}). The subscripts, $th.e^-$, $ps.e^-$, H^+, p^+ and O^+ refer to the ionospheric and plasma sheet electrons, the ionospheric and plasma sheet protons, and the ionospheric oxygen ions. The fluxes are positive for the outward flowing particles of ionospheric origin, and negative for the inward flowing plasma sheet particles.

The velocity distributions of all these particles are represented by isotropic Maxwellian functions which are characterized by temperatures T_j and densities n_j. At the plasma sheet side of the magnetic field line (i.e. in the equatorial plane) the following boundary conditions for the plasma sheet particles are adopted (Vasyliunas, 1970):

$$T_{ps.e^-} = 10^7\ {}^\circ\mathrm{K}, \quad T_{p^+} = 5 \times 10^7\ {}^\circ\mathrm{K}, \quad \text{and} \quad n_{ps.e^-} = n_{p^+} = 0{\cdot}1\ \mathrm{cm}^{-3}.$$

Near the Earth's end of this field line the ionospheric ion densities are taken from OGO 2 observations at an altitude of $\simeq$1000 km above the auroral region (Taylor *et al.*, 1968)

$$n_{\mathrm{O}^+} = 2 \times 10^3\ \mathrm{cm}^{-3}, \quad n_{\mathrm{H}^+} = 2 \times 10^2\ \mathrm{cm}^{-3}, \quad n_{th.e^-} = 2{\cdot}2 \times 10^3\ \mathrm{cm}^{-3}.$$

From the Alouette 1 experimental electron density scale height determinations (H $\simeq$ 600 km) (Thomas *et al.*, 1966) and from *mean ion mass* determinations above the auroral zone ($\bar{m}_i \simeq 14$) by OGO 2 (Taylor *et al.*, 1968), it can furthermore be deduced that $\frac{1}{2}(T_{th.e^-} + T_{\mathrm{O}^+}) = 3000\ {}^\circ\mathrm{K}$ at 1000 km altitude. Therefore the applied boundary conditions at 1000 km

$$T_{th.e^-} = 4500\ {}^\circ\mathrm{K}, \qquad T_{\mathrm{O}^+} = 1500\ {}^\circ\mathrm{K}, \qquad T_{\mathrm{H}^+} = 4000\ {}^\circ\mathrm{K}$$

are consistent with the available observational data. These temperature values, already used by Lemaire (1971) in a new polar wind model, fit the ion-densities and fluxes observed at 3000 km altitude by Explorer 31 (Hoffman, 1971) and the OGO 2 measurements at a lower polar altitude (Taylor *et al.*, 1968).

For the ionospheric electron and ion populations, the incoming particles with a kinetic energy larger than the total potential energy between the equator and the low altitude end of a given magnetic field line are ignored in the velocity distribution. This means that, for these energies, the pitch angle (α) distribution is empty in the downward loss cone, i.e. for $180° - \theta_m < \alpha < 180°$ where θ_m is the loss cone angle ($\theta_m = 90°$ at the baropause altitude which is 1000 km in our exospheric model). Thus we neglect the contribution of the ionospheric particles from the conjugate auroral region although some of these particles can reach the equatorial altitudes and flow into the other hemisphere. Since the transit time of a thermal H^+ ion from one hemisphere to the other along an auroral magnetic field is larger than the characteristic time of the ionospheric variations or of losses by charge exchange the contribution of these conjugate ionospheric particles have been ignored in the high latitude ion-exosphere. If these particles are included, as they are in the exospheric plasmasphere models of Eviatar *et al.* (1964) and of Hartle (1969), no supersonic outflow of H^+ ions would result in the topside auroral ionosphere. This is contrary to the conclusion obtained by Brinton *et al.* (1971) for the midlatitude region ($L = 5$–$10{\cdot}5$) where the observations suggest such an upward proton flow.

For the plasma sheet particles, on the contrary, the pitch angle distribution is truncated in order to neglect the particles in the upward loss cone, i.e. $0 < \alpha < \theta_m$ (with $\theta_m \sim 1°$ in the equatorial plane, and $\theta_m = 90°$ at the baropause). This means that the precipitated plasma sheet particles with mirror points below the baropause are not reflected, but scattered and lost by inelastic collisions.

As the ions and electrons are assumed to be collisionless their magnetic moment (first adiabatic invariant) and total energy are conserved, and Liouville's or Vlasov's equation can be integrated with the above described velocity distributions as boundary conditions.

The electric potential distribution $\phi_E(h)$ along the magnetic field line is determined in order to maintain the local and global quasineutrality (equations 1 and 2). The method of calculation which has been described by Lemaire and Scherer (1970, 1971) for a three-component ion-exosphere (O^+, H^+ and thermal electrons, henceforward called model A) can also be applied to the present case where the plasma sheet electrons and protons are additional constituents (model B).

NUMERICAL RESULTS

The solid and dashed lines in Fig. 2 show the parallel electric field distribution, $\vec{E}_{||} = -\vec{\nabla}_{||}\phi_E$, as a function of altitude (left hand scale) and as a function of latitude (right hand scale) for the models A and B. It can be seen that the presence of suprathermal particles (model B) has no influence in the lower altitude range where the ionospheric particles are largely predominant. At larger radial distances however the plasma sheet particles contribute more significantly to the total charge density and reduce the intensity of the upward directed electric field. It is worthwhile to note that in the double-layer model of Hultqvist (1971, 1972) the electric field is directed downwards, and that the potential difference between the ionosphere and the plasma sheet is +600 V, while in our model B it remains small ($-2{\cdot}8$ V).

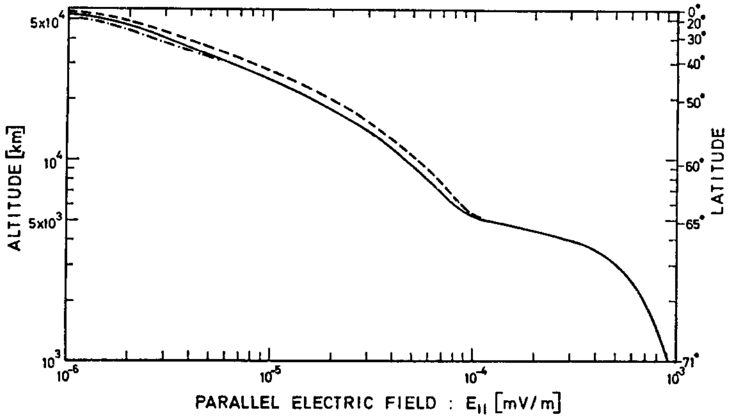

Fig. 2. The polarization electric field component parallel to the magnetic field direction (m V/m) in model A (dashed line; without plasma sheet particle precipitation), in model B (solid line; with plasma sheet particle precipitation along the magnetic field line $\Lambda = 71°$) and in model C (dotted-dashed line; for a field aligned current of $4{\cdot}9 \times 10^{-6}$ A/m^2).

The density distributions for model B are shown in Fig. 3. The ionospheric ion densities in model B are approximatively the same as in model A (although the latter is not illustrated in Fig. 3). The plasma sheet particle densities increase slowly with altitude. This is due to the plasma sheet particles which mirror at high altitudes and do not contribute to the density at the lower levels.

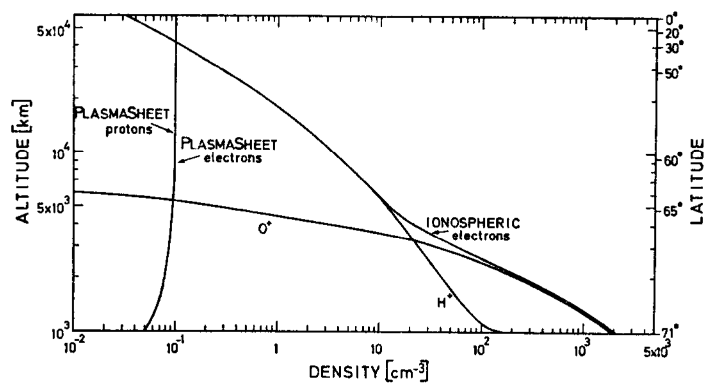

Fig. 3. Density distributions of the oxygen and hydrogen ions, and of the electrons of ionospheric origin. The density distributions of the plasma sheet protons and electrons in the kinetic model B, along the magnetic field line $\Lambda = 71°$ are also shown.

It can be seen that close to the equatorial plane the 'hot' plasma density becomes larger than the 'cold' (ionospheric) plasma density. This is consistent with Vasyliunas' (1969) conclusion that the very low energy (thermal or ionospheric) electron density is smaller than the density of the electrons (0·05–50 keV) that has been observed in the plasma sheet.

Figure 4 shows the bulk velocity of the different kinds of particles in model B. The solid curves corresponds to positive values (outward velocities of the ionospheric particles) while the dotted lines correspond to negative values of w (inward bulk velocities of the

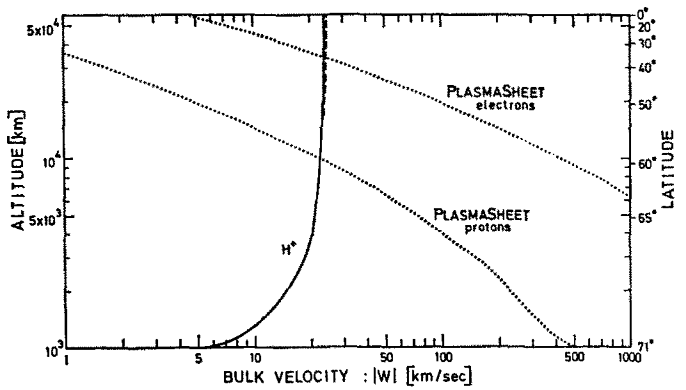

FIG. 4. UPWARD BULK VELOCITY OF IONOSPHERIC HYDROGEN IONS (SOLID LINE); DOWNWARD BULK VELOCITY OF THE PLASMA SHEET PROTONS AND ELECTRONS IN THE KINETIC MODEL B, ALONG THE MAGNETIC FIELD LINE $\Lambda = 71°$

plasma sheet particles). It can be seen that the outward flow of the H^+ ions becomes supersonic as in model A (dashed line) where the plasma sheet particles were ignored. The asymptotic value of w_{H^+} is only slightly reduced as a consequence of the smaller accelerating parallel electric field in model B. The O^+ ion bulk velocity is not shown in Fig. 4 since it is very small.

The *downward* bulk velocities of the plasma sheet protons and electrons increase with decreasing altitudes as if these particles were individually accelerated by a parallel electric field like that proposed by Hultqvist (1971, 1972) to precipitate the auroral protons. It is, however, not a consequence of an individual particle acceleration, but is due to the convergent geometry of the flux tubes. As the densities $n_{ps.e^-}$ and n_{p^+} are nearly independent of altitude (see Fig. 3) and, since the cross section of the magnetic tubes increases approximately as the cube of the radial distance r, the continuity equation yields

$$|w_{ps.e^-(p^+)}| \sim r^{-3}.$$

The increase of the bulk velocity with decreasing altitude can also be understood in terms of the particle pitch angle distribution and a 'magnetic filtering' effect. Indeed the ratio of the precipitated (α inside the downward loss cone; contributing to the flux F) to the mirroring plasma sheet particles (α outside the loss cone; not contributing to F) increases with decreasing altitude. For the plasma sheet temperatures of model B the values of $w_{ps.e^-}$ and w_{p^+} are respectively $-9{\cdot}8 \times 10^3$ km/sec and -510 km/sec at the top of the atmosphere.

The downward proton mean velocity observed by the Doppler shift of Hα sometimes emitted in auroral displays is typically 300–500 km/sec (Chamberlain, 1961, p. 207) and therefore of the same magnitude as in our theoretical estimation.

From the second order moments of the velocity distribution it is possible to deduce parallel and perpendicular temperatures T'' and $T^{\perp}$, for each type of particles. These parameters, which are useful to characterize the dispersion of the velocity distributions, have been calculated in model B. It is found that, for the plasma sheet particles, average temperatures, $\langle T\rangle = \frac{1}{3}(T'' + 2T^{\perp})$, do not change much from their plasma sheet values ($T_{ps.e^-} = 10^7$ °K and $T_{p^+} = 5 \times 10^7$ °K) down to the auroral region. The 'temperature' is isotropic in the plasma sheet ($T''/T^{\perp} = 1$) but becomes anisotropic near the baropause ($T''/T^{\perp} = 0{\cdot}36$).

The profile of Hα emission, resulting from proton bombardment of the auroral atmosphere, has a half-width Doppler temperature of 3–4 $\times$ 10^7 °K in the auroral spectra photographed at a 90° zenith angle (Chamberlain 1961, p. 206 and Fig. 5.19). The observed temperature corresponds to the perpendicular proton temperature, $T_{p^+}^{\perp}$, in our kinetic model. Both values coincide for plasma sheet protons with a mean energy of 3–4 keV. Furthermore the lack of large variation in $T_{p^+}^{\perp}$ with height suggests the altitude dependence of the observed Hα horizontal Doppler profiles (Chamberlain, 1961, p. 256).

DISCUSSION

The precipitation fluxes F (particles/cm² sec) calculated in model B are respectively

$$F_{ps.e^-} = -4 \cdot 9 \times 10^7 \text{ cm}^{-2}\text{ sec}^{-1} \quad \text{and} \quad F_{p^+} = -2 \cdot 5 \times 10^6 \text{ cm}^{-2}\text{ sec}^{-1}$$

at 1000 km altitude.

Spacecraft measurements usually give directional fluxes $J(\alpha)$. When the pitch angle distribution is isotropic, J is independent of the angle α, and $|F| = \pi J$. Therefore in model B we have

$$J_{ps.e^-} = 1 \cdot 6 \times 10^7 \text{ cm}^{-2}\text{ sec}^{-1}\text{ str}^{-1} \quad \text{and} \quad J_{p^+} = 8 \cdot 0 \times 10^5 \text{ cm}^{-2}\text{ sec}^{-1}\text{ str}^{-1}$$

and the energy fluxes are

$$\varepsilon_{ps.e^-} = -0 \cdot 14 \text{ erg cm}^{-2}\text{ sec}^{-1} \quad \text{and} \quad \varepsilon_{p^+} = -0 \cdot 035 \text{ erg cm}^{-2}\text{ sec}^{-1}.$$

These calculated values are comparable to the lowest precipitation fluxes observed during magnetically quiet time at the low latitude boundary of the auroral region by Frank and Ackerson (1971) or by Heikkila (1971).

Although these 1 keV electron fluxes probably have sufficient intensity to account for the 'drizzle' precipitations (Hartz, 1971) and to produce the mantle aurora or ionospheric radio wave absorption (Sharber and Heikkila, 1972), they are however too low to explain visible auroral displays (Chamberlain, 1961, p. 197, p. 253). The softer electron precipitation fluxes observed during the night and at a somewhat higher latitude are often larger and may occasionally be enhanced by more than one order of magnitude (Sharber and Heikkila, 1972) during magnetic substorm activity.

Models with larger particle precipitation fluxes and downward energy fluxes can be obtained by increasing the density and/or the mean energy of the plasma sheet particles at the equator end of the magnetic field line. When the plasma sheet electron flux is smaller than the total ion flux (which is mainly carried by the outflowing H^+ ions)

$$F_{\text{ion}} \simeq F_{H^+} = \tfrac{1}{2}\, n_{H^+}(8kT_{H^+}/\pi m_{H^+})^{1/2}, \tag{3}$$

the electric field distribution (Fig. 2) and the ionospheric ion density and bulk velocity distributions (Figs. 3 and 4) are not much different from the corresponding values of model A where $F_{H^+} = 10^8$ cm^{-2} sec^{-1} at 1000 km. ($n_{H^+} = 2 \times 10^2$ cm^{-2} and $T_{H^+} =$ 4000 °K). However, much larger precipitation fluxes of plasma sheet electrons ($F_{ps.e^-} > 10^8$ cm^{-2} sec^{-1}) can remain partially unbalanced by the upward thermal electron flux and consequently a field aligned current, j'', will flow along the magnetic field lines. Such field aligned currents can easily be included in our model calculations by assuming that the total electron flux in Equation (2) does not balance the flux of positively charged particles

$$\sum_i Z_i F_i = F_c = j''/e \tag{4}$$

where $Z_i = -1$ for the electrons and $Z_i = +1$ for the charged positive ions. F_c is the unbalanced part of the total flux.

A plasma sheet precipitation flux of $3{\cdot}1 \times 10^9$ cm^{-2} sec^{-1}, as observed by Vondrak *et al.* (1971) in an auroral arc, can for instance be obtained with plasma sheet electron and ion densities of $6{\cdot}3$ cm^{-3} (instead of $0{\cdot}1$ cm^{-3} as in model B) and the same temperature conditions as in model B. For these new equatorial boundary values and for a field aligned current of $4{\cdot}9 \times 10^{-6}$ A/m^2 (i.e. $F_c = 3 \times 10^9$ cm^{-2} sec^{-1} in Equation 4) the electric field distribution in this model C (shown by the dotted dashed line in Fig. 2) is nearly the same as in model B. Although the precipitated particle and energy fluxes in model C are 63 times larger than in model B and now comparable to the values required to produce visible auroral displays (Chamberlain, 1961, p. 197, p. 253), the bulk velocities and 'temperatures' distributions are not significantly changed because the mean kinetic energy of the particles are the same in both models C and B.

Therefore, if field aligned currents are allowed to flow along the magnetic field lines, the electric potential distribution in the ion exosphere is not drastically changed and the ionospheric particle distributions are not necessarily affected by the assumption $F_c \neq 0$ or $j'' \neq 0$ in Equation (4).

Block (1972), however, has shown that for field aligned currents larger than a critical value, j''_{crit} a stable double-layer can appear and account for the sharp 'monoenergetic' peaks in the electron energy spectrum occasionally observed above discrete auroral arcs (Westerlund, 1969; Evans, 1967, 1969; Chase, 1969). For the boundary conditions in the models A or B ($n_{th.e^-} = 2{\cdot}2 \times 10^3$ cm^{-3}, $T_{th.e^-} = 4500$ °K) this critical current at 1000 km is given by

$$j''_{\text{crit.}} = en_e(2\gamma kT_{th.e^-}/m_{e^-})^{1/2} = 1{\cdot}8 \times 10^{-4}\ \text{A/m}^2$$

where γ is the ratio of specific heats and corresponds to an electron flux of $1{\cdot}1 \times 10^{11}$ cm^{-2} sec^{-1} which is larger than that usually observed. Note however that field aligned currents up to about 10^{-4} A/m^2 have been deduced from observations by Zmuda *et al.* (1970). Kindel and Kennel (1971) argue that ion cyclotron waves become unstable at even lower values of the field aligned current ($j^{\parallel} > 10^{-5}$ A/m^2).

In model B and C discussed above it was assumed that the velocity distribution of the plasma sheet particles was isotropic (except in the upward loss cone). Asymmetric and/or anisotropic velocity distributions may also be introduced as boundary conditions (Lemaire and Scherer, 1972) in order to get the anisotropic auroral precipitation patterns sometimes observed (Hultqvist *et al.*, 1971; Holmgren and Aparicio, 1972; Frank and Ackerson, 1971; Hones *et al.*, 1971). It must however be noted that it is not always necessary to assume that the pitch angle distribution is *anisotropic* at the equator to obtain, at auroral altitudes, parallel particle fluxes which are different from the fluxes in the direction perpendicular to the magnetic field (i.e. $J'' \lessgtr J^{\perp}$). Indeed even with an isotropic velocity distribution for the plasma sheet protons, rapid time enhancements (or decreases) of the density (n_{p^+}) and/or of the temperatures (T_{p^+}), will result in transient larger (or smaller) values of J'' compared to $J^{\perp}$. This is a consequence of the smaller flight time of protons with small pitch angles compared to those with $\alpha \simeq 90°$. For a 5 keV proton the flight time from the equator to the auroral latitude is 90 sec for $\alpha = 0°$ and 10 sec more for $\alpha = 89°$. Field aligned anisotropies in the proton precipitation flux are therefore expected during the 10 sec following a proton event. Such an event may have been observed by Frank and Ackerson (1971, plate 3a) when the proton flux and mean energy increased in a time of 12 sec at 03 h 30 m 55 UT during Revolution 1573 of INJUN 5.

For a 1 keV electron the flight time is only 5 sec for $\alpha = 0°$ and 500 msec more for $\alpha = 89°$. Frank and Ackerson (1971, Fig. 6) have reported one event where the increase of intensity of precipitated electrons (J_{e-}'') precede the corresponding increase of the 90° pitch angle electrons ($J_{e-}^{\perp}$) by 200 msec.

Although these qualitative considerations seem to fit some observed features of aurora particle precipitation, time dependent models are needed to get a more quantitative representation of the strong and 'splash' auroral events.

CONCLUSIONS

The validity of the stationary model described above is restricted to slowly varying particle precipitation patterns. Auroral events with time constants smaller than 1 min (i.e. the flight time of the protons) need non-stationary models which are not available at the present time. It is not excluded that, in time dependent models, a double-layer as suggested by Block (1972) may appear at the edge of an invading dense plasma cloud, and that large electric currents flowing along the line of force during strong electron precipitation (Boström, 1964; Taylor and Perkins, 1971; Park and Cloutier, 1971) destabilize the ion cyclotron waves, providing occasionally anomalous resistance in the topside ionosphere as suggested by Kindel and Kennel (1971).

However, for boundary values representative of the observed plasma sheet and ionospheric normal conditions, the local quasi-neutrality and near-zero-electric current conditions can be satisfied without any large electric potential difference along the auroral geomagnetic field line. This result agrees with one of the conclusions that Coronoti and Kennel (1972) deduced recently from a different point of view.

Therefore, the magnetic field lines are approximately equipotential lines, with the consequence that any magnetospheric transverse electric potential gradient may be projected along the geomagnetic field lines downward to the auroral ionosphere where it results in a horizontal electric field ($E_{\perp}$).

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