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IONOSPHERE–PLASMASHEET FIELD–ALIGNED CURRENTS AND PARALLEL ELECTRIC FIELDS

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Abstract—Two kinetic models for the auroral topside ionosphere are compared. The collisionless plasma distributed along an auroral magnetic field line behaves like a non-Ohmic conducting medium with highly non-linear characteristic curves relating the parallel current density to the potential difference between the cold ionosphere and the hot plasmasheet region. The (zero-electric current) potential difference, required to balance the current carried by the precipitating plasmasheet particles and the current transported by the outflowing ionospheric particles, depends on the ratio $n_{ps.e}/n_{th.e}$ and $T_{ps.e}/T_{th.e}$ of the plasmasheet and ionospheric electron densities and temperatures. When in the E-region the magnetic field lines are interconnected by a high conductivity plasma the resulting field-aligned currents driven by the magnetospheric potential distribution are limited by the integrated Pedersen conductivity of the ionospheric layers. These currents are not related to the parallel electric field intensity as they would be in Ohmic materials. The parallel electric field intensity is necessarily determined by the local quasi-neutrality of the plasma.

1. INTRODUCTION

The existence of parallel electric fields along the magnetic field lines connecting the auroral ionosphere and the plasmasheet is an important problem in magnetospheric physics. Hultqvist (1971, 1972) deduced from a collision-dominated model calculation that the electric potential of the plasmasheet should be about 600 V higher than the ionospheric potential to cancel the Ohmic electric current driven downwards by a thermoelectric field $E_{\|}$. This field results mainly from the electron temperature gradient. In a collision-dominated plasma this polarization electric field comes from the tendency for the electrons to diffuse out of the high temperature regions (plasmasheet) towards the colder regions (ionosphere). The validity of such a model rests upon the assumption that the collision rate of the ionospheric and plasmasheet electrons is sufficiently large so that their velocity distribution is sufficiently close to the Maxwell distribution and that the transport coefficients (e.g. the electrical conductivity, the thermal diffusion coefficient, . . .) can still be calculated from the classical Chapman–Enskog first order approximation. In the topside auroral ionosphere, above *ca.* 1000 km altitude, the electron density ($n_{th.e}$) is smaller than 2×10^3 cm^{-3}, and the electron temperature ($T_{th.e}$) is larger than 2×10^3 °K. Therefore the Coulomb collisions become so infrequent that the Chapman–Enskog method for estimating the transport coefficients becomes as useless as the classical hydrodynamic approximations themselves (Lemaire and Scherer, 1973b). Unless it will be proven that enough electromagnetic (resonant) wave energy is stored in the magnetospheric flux tubes to scatter all the exospheric particles, and that a generalized Ohm law relates the electric current density to the parallel electric field, collision dominated models for the topside ionosphere remain very questionable.

On the other hand kinetic models of the relatively cold ionospheric plasma ($T_{th.e} = 10^3 - 10^4$ °K) penetrated by hot plasmasheet particles ($T_{ps.e} = 10^6 - 10^7$ °K) have been presented by Lemaire and Scherer (1973a) and by Knight (1973). In both models the plasmasheet electric potential (ϕ_S) is lower than the ionospheric potential (ϕ_E). The reduced electric potential difference $x = e(\phi_E - \phi_S)/kT_{th.e}$ is determined by Knight as a function of the electric current carried by the precipitating suprathermal electrons, and by the thermal

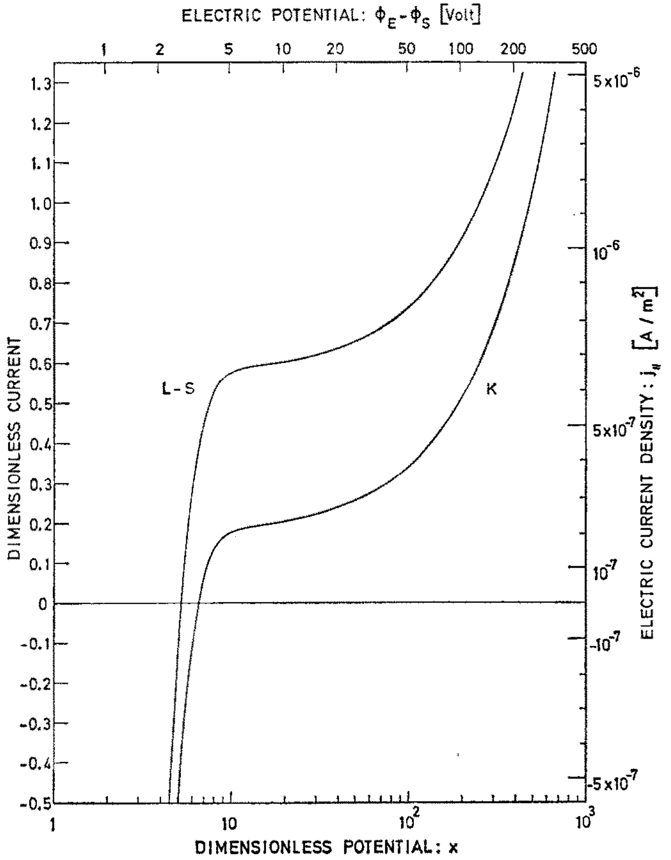

FIG. 1. PARALLEL ELECTRIC CURRENT DENSITY AS A FUNCTION OF THE ELECTRIC POTENTIAL DIFFERENCE BETWEEN THE IONOSPHERE (E) AND THE PLASMASHEET (S).

The density and temperature of the thermal electrons at the ion exobase are respectively: $n_{th.e} = 10^3$ cm^{-3} and $T_{th.e} = 6000$°K. The density and temperature of the plasmasheet electrons at the equatorial end of the magnetic line of force are respectively given by $n_{ps.e} = 10^{-3}\, n_{th.e}$, and $T_{ps.e} = 10^2\, T_{th.e}$.

It was also assumed that the equatorial cross section, A_s, of the auroral flux tubes is 1000 times larger than A_E, its cross-section in the ionosphere: $A_S/A_E = B_E/B_S = 10^3$.

The field-aligned current is zero for a potential difference of 3·39 V in Knight's (1973) model K, and for $\phi_E - \phi_S = 2{\cdot}69$ V in the model L–S of Lemaire and Scherer (1973).

Note the non-linearity of the Electrical Characteristics of the collisionless plasma distributed along an auroral field line.

electrons evaporated from the topside ionosphere. Curve K in Fig. 1 illustrates Knight's results in dimensionless variables: the electric potential is given in $kT_{th.e}/e$ units, and the electric current in $n_{th.e}e(kT_{th.e}/m_{\mathrm{H}^+})^{1/2}$ units, with the convention that positive values correspond to electric currents flowing away from the Earth. (Note that the reverse convention is used in Knight's paper). The upper and R.H.S. scales give respectively the potential $\phi_E - \phi_S$ and the field-aligned current $j_\parallel$ in V and in A/m^2 for $T_{th.e} = 6000$°K and $n_{th.e} = 10^3$ cm^{-3}. The results illustrated in Fig. 1 were obtained for $n_{ps.e}/n_{th.e} = 10^{-3}$, $T_{ps.e}/T_{th.e} = 10^2$ and $B_E/B_S = 10^3$. It can be seen that the electric current given by curve K is zero for $x = X_0 = 6{\cdot}56$ or $\phi_E - \phi_S = 3{\cdot}39$ V.

Curve L–S in Fig. 1 corresponds to a calculation made by the present authors by using the model of Lemaire and Scherer (1973a) when the same boundary conditions are used as in the previous case. The field-aligned current now becomes zero for $X_0 = 5{\cdot}21$; i.e. for $\phi_E - \phi_S = 2{\cdot}69$ V. For values of the dimensionless potential smaller than X_0 the current is negative (i.e. toward the Earth) as a consequence of a large escape flux of the ionospheric electrons. For $x > X_0$ the net current is directed away from the Earth since the larger potential barrier reduces the flux of the escaping thermal electrons below the value of the precipitated plasmasheet electron flux. Both curves in Fig. 1 resemble the *characteristics* of a thermionic tube where the electric current is a highly non-linear function of the potential difference between the cold ionosphere and the hot plasmasheet region. The difference between Knight's results and those of Lemaire and Scherer, illustrated in Fig. 1, is due to differences in the kinetic model descriptions. Indeed, besides the current carried by the electrons considered by Knight, Lemaire and Scherer also took into account the current transported by the ionospheric ions (H^+) and by the plasmasheet protons (p^+). When the total net current is small the H^+ escape flux makes a contribution to $j_{\|}$ which cannot be neglected despite the lower mobility of the ions compared to the electron mobility. Indeed if the fluxes of plasmasheet and ionospheric electrons nearly balance each other, the hydrogen ion flux will significantly contribute to the net field-aligned current. Knight's assumption that "the electrons make the dominant contribution to the net electric current" is therefore only valid for $x > 10^4$, i.e. for very large current densities $j_{\|} \simeq 2 \times 10^5$ Am^{-2}. In this large current regime the models K and L–S provide equivalent results.

2. ZERO-CURRENT CONDITION

The characteristics shown in Fig. 1, as well as the value of X_0 for which $j_{\|} = 0$, depend on the relative densities and temperatures of the plasmasheet and ionospheric particles. Figure 2 illustrates the dependence of X_0 on the ratio $n_{ps.e}/n_{th.e}$ for a constant value of

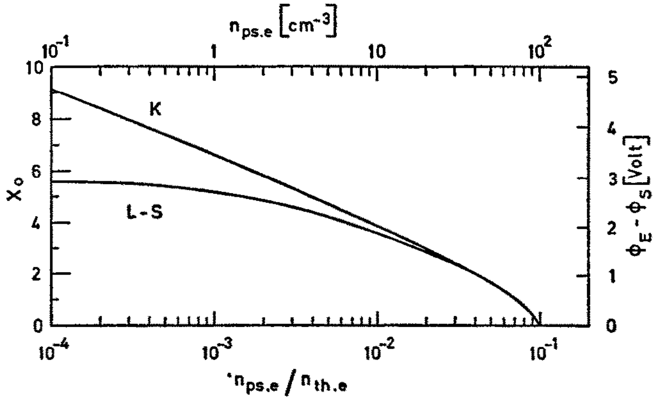

FIG. 2. ELECTRICAL POTENTIAL DIFFERENCE BETWEEN THE IONOSPHERE (E) AND THE PLASMASHEET (S) REQUIRED TO BALANCE THE UPWARD AND DOWNWARD CURRENTS CARRIED BY THE HOT PLASMASHEET AND COLD IONOSPHERIC PARTICLES (i.e.: $\Sigma j_{\|} = 0$).

As for Fig. 1 it is assumed that $n_{th.e} = 10^3$ cm^{-3}, $T_{th.e} = 6000$°K, $T_{ps.e}/T_{th.e} = 10^2$, $A_S/A_E = B_E/B_S = 10^3$. The density of the precipitating plasmasheet electrons is varied from $n_{ps.e} = 10^{-1}$ to 10^2 cm^{-3}. In Knight's (1973) model K where the current transported by the H^+ ions is neglected, the potential difference for a zero electric current increases indefinitely when $n_{ps.e}$ tends to zero, while in the (1973) model L–S of Lemaire and Scherer it has a maximum value: $[\phi_E - \phi_S]^{\max} = 2{\cdot}92$ V. For $n_{ps.e} \geqslant 10^2$ cm^{-3}, the potential difference for zero electric current becomes negative and the flux of precipitating electrons is larger than the threshold for formation of double layers (Block, 1972) or for driving the ion-cyclotron waves unstable (Kindel and Kennel, 1971).

$T_{ps.e}/T_{th.e} = 10^2$. The upper and R.H.S. scales give the corresponding values of $n_{ps.e}$ and $(\phi_E - \phi_S)$ when $n_{th.e} = 10^3$ cm^{-3} and $T_{th.e} = 6000$°K. It can be seen that in the model L–S, X_0 reaches a maximum value $X_0^{\max} = 5{\cdot}64$ (or $(\phi_E - \phi_S)^{\max} = 2{\cdot}92$ V), which corresponds to a zero plasmasheet density. At this limit the escape fluxes of the thermal electrons and ionospheric hydrogen ions balance each other as in the polar wind model of Lemaire and Scherer (1969, 1970). In Knight's approximation, where the H$^+$ ion flux was neglected, $X_0^{\max} = \infty$. On the other hand when the plasmasheet density and precipitation flux become large, the potential difference $(\phi_E - \phi_S)$ decreases slowly and becomes equal to zero for $n_{ps.e}/n_{th.e} = 0{\cdot}1$. At this limit the precipitation flux of the plasmasheet electrons is approximately equal to the maximum escape flux of the thermal electrons:

$$F_{ps.e} \approx -F_{th.e}^{\max} = -n_{th.e}\sqrt{\frac{2kT_{th.e}}{\pi m_e}}.$$

This maximum value corresponds to the critical electron flux for which Block (1972) has shown that a double potential layer can occur between the ionosphere and the plasmasheet region. For $T_{th.e} = 6000$°K and $n_{th.e} = 10^3$ cm^{-3} we have $F_{th.e}^{\max} = 2{\cdot}4 \times 10^{10}$ cm^{-2} sec^{-1} which corresponds to partial current densities of $j_{ps.e}^{\parallel} \simeq -j_{th.e}^{\parallel} = 4 \times 10^{-5}$ A/m^2. This is larger than the usually observed values. For plasmasheet densities larger than $n_{ps.e}^{\max} = 0{\cdot}1\ n_{th.e}$ (i.e. $n_{ps.e} > 10^2$ cm^{-3}), X_0 becomes negative and a minimum in the electric potential will appear somewhere along the field line to reduce the precipitation flux of the energetic electrons and confine them near the equatorial plane between two potential barriers located in both hemispheres. Kindel and Kennel (1971) argued that ion cyclotron waves already become unstable for precipitation fluxes larger than 10^9–10^{10} cm^{-2} sec^{-1}. In this case strong wave particle interactions will change the physical properties of the plasma, and the assumptions on which the kinetic models are based will no more be applicable for the resonant particles.

3. MODELS WITH FIELD-ALIGNED CURRENTS

In the preceding section it was assumed that no net electric current can flow along any field line. This implies that the field lines are electrically insulated from each other. The thermoelectric potential difference $\phi_E - \phi_S$, arising between the equatorial and ionospheric "ends", is then comparable to the potential difference between the cold anode (ionosphere) and the heated cathode (plasmasheet) in an unpolarized thermionic tube. In the magnetosphere–ionosphere system the Pedersen conductivity becomes large in the lower ionospheric E-region, and adjacent field lines are not insulated but electrically interconnected. If at the equatorial ends of the field lines an electric potential difference is applied a current will flow up and down along the good conductivity "wire" constituted by the magnetic field lines. The current density driven by the convection magnetospheric potential distribution will be determined or limited by the integrated Pedersen conductivity of the ionosphere which constitutes the load or resistance of this large scale electric circuit system. In this model, which was discussed by Boström (1972), the convection electric potential distribution predicted by Axford and Hines (1961) and determined experimentally by McIlwain (1972) can be considered as a generator or a battery whose electromotive force is changing with time and related to the solar wind velocity and magnetic field orientation. Nevertheless, it is clear that the small potential difference $(\phi_E - \phi_S)$ does not drive the currents up and down along the field lines. The value of $(\phi_E - \phi_S)$ will continuously adjust to the current $j_{\parallel}$, and not the reverse as is sometimes believed. Indeed, only a small adjustment of the potential barrier $e(\phi_E - \phi_S)$ can provide any value for the thermal electron escape flux which ranges between $F_{H^+} = n_{H^+}(2kT_{H^+}/\pi m_{H^+})^{1/2} \simeq 5 \times 10^8$ cm^{-2} sec^{-1} and $F_{th.e}^{max} \approx 2{\cdot}4 \times 10^{10}$ cm^{-2} sec^{-1}. The lower limit which corresponds to a maximum of the potential, i.e. 2·9V, yields a parallel electric current density of 5×10^{-6} Am^{-2} for a plasmasheet particle precipitation flux of -3×10^9 cm^{-2} sec^{-1} as observed by Vondrak *et al.* (1971). The upper limit corresponds to a nearly zero potential difference between the upper ionosphere and the plasmasheet, and yields a downward electric current density of $-3{\cdot}3 \times 10^{-5}$ Am^{-2}. The usually observed Birkeland currents measured by Zmuda *et al.* (1970), Armstrong and Zmuda (1970), and reviewed by Cloutier (1971), are of the same order of magnitude.

6. THE PARALLEL ELECTRIC FIELD

In Knight's paper the ion density distributions and the local quasi-neutrality condition of the exospheric plasma are not discussed. Nevertheless, an arbitrary electric potential distribution, $\phi(r)$, or an arbitrary parallel electric field $[E_{\|} = -\nabla_{\|}\phi(r)]$, will generally lead to an electron density n_e, and a scale height H_e, which differ from the total ion density $\sum_{ion} n_i$, and the ion scale height H_i. As a consequence an unrealistic electric space charge density would exist in the whole exosphere. Indeed, the actual parallel electric field in a plasma determines the electron and ion density gradients or scale heights along the magnetic field lines. At each altitude there is a unique value of $E_{\|}$ such that $\nabla_{\|}n_e = \nabla_{\|} \sum_{ion} n_i$, and $n_e = \sum_{ion} n_i$. There are many electric field distributions $E_{\|}$ which will give the same value of $\phi_E - \phi_S = -\int_{r_S}^{r_E} E_{\|}$ ds. But there is only one distribution which will provide the local quasi-neutrality of the plasma between the exobase (r_E) and the equational plane (r_S) and which satisfies Poisson's equation. Lemaire and Scherer (1973a) have calculated this parallel electric field distribution along an auroral field line for realistic electron and ion (H^+, O^+) densities and temperatures in the ionosphere and in the plasmasheet. They found that $E_{\|}$ decreases with altitude and always remains smaller than 10^{-3} mV/m. The value of the potential difference between the exobase and the plasmasheet corresponding to a zero field aligned current is $(\phi_E - \phi_S) = 2{\cdot}8$ V. By neglecting the ionic current as in Knight's model it follows that $(\phi_E - \phi_S) = 3{\cdot}25$ V for the same boundary conditions. In the calculations of Lemaire and Scherer the plasmasheet particle densities are $n_{ps.e} = n_{p^+} = 0{\cdot}1$ cm^{-3} and the precipitation fluxes are respectively $F_{ps.e} = -4{\cdot}9 \times 10^7$ cm^{-2} sec^{-1}, $F_{p^+} = -2{\cdot}5 \times 10^6$ cm^{-2} sec^{-1} at the reference level of 1000 km. These values which correspond to the lowest precipitation fluxes observed at the low latitude boundary of the auroral zone by Frank and Ackerson (1971) and by Heikkila (1972, 1973), are too small to explain visible auroral displays (Chamberlain, 1961). When the plasmasheet electron density or temperature are increased by an amount $\Delta n_{ps.e}$ or $\Delta T_{ps.e}$ respectively, the precipitation flux will increase by an amount $\Delta F_{ps.e}$. To maintain the potential barrier $e(\phi_E - \phi_S)$ the thermal electrons have to overcome, a Birkeland current must be able to flow out of the ionosphere. The density of this field-aligned current is then related to the excess $\Delta F_{ps.e}$ of the plasmasheet electron flux by $j_{\|} = -e\Delta F_{ps.e}$. For a precipitation flux of $-3{\cdot}1 \times 10^9$ cm^{-2} sec^{-1}, $j_{\|}$ must be equal to $4{\cdot}9 \times 10^{-6}$ A/m^2 in order to obtain the same potential difference as in the previously discussed model where $\Delta n_{ps.e}$, $\Delta F_{ps.e}$ and $j_{\|}$ are zero. Quite the same parallel electric field distribution and ionospheric ion density distributions are then obtained.

Whether or not such a current can flow along the field line will depend on the conductivity in the lower ionosphere and on the electrostatic potential distribution in the equatorial plane. When the resistance of the ionosphere is too large (small) the current density will be smaller (larger) than $-e\Delta F_{ps,e}$ and the potential difference ($\phi_E - \phi_S$) will decrease (increase) in order to enhance (diminish) the thermal electron escape flux.

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