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Field aligned current density versus electric potential
characteristics for magnetospheric flux tubes

by

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B E L G I S C H I N S T I T U U T V O O R R U I M T E - A E R O N O M I E

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FOREWORD

The text "Field aligned current density versus electric potential characteristics for magnetospheric flux tubes" will be published in the journal of the European Geophysical Society (EGS) : "Annales Geophysicae". This paper has been presented at the IAGA symposium : Polar Cusp and Magnetosphere Boundary Layers (Edinburgh, 3-15 August, 1981).

AVANT-PROPOS

L'article intitulé "Field aligned current density versus electric potential characteristics for magnetospheric flux tubes" sera publié dans le journal de la Société Européenne de Géophysique (EGS) : "Annales Geophysicae". Ce travail a été présenté au symposium de l'IAGA : Polar Cusp and Magnetosphere Boundary Layers, (Edinburgh, 3-15 août, 1981).

VOORWOORD

De tekst "Field aligned current density versus electric potential characteristics for magnetospheric flux tubes" zal uitgegeven worden in het tijdschrift van de European Geophysical Society (EGS) : "Annales Geophysicae". Dit werk werd voorgesteld tijdens het symposium van de IAGA : Polar Cusp and Magnetosphere Boundary Layers, (Edinburgh, 3-5 August, 1981).

VORWORT

Der Text "Field aligned current density versus electric potential characteristics for magnetospheric flux tubes" wird in dem Buch von der European Geophysical Society (EGS) : "Annales Geophysicae" herausgegeben werden. Diese Arbeit wurde präsentiert während der Tagung von IAGA : Polar Cusp and Magnetosphere Boundary Layers, (Edinburgh, 3-5 August, 1981).

FIELD ALIGNED CURRENT DENSITY VERSUS ELECTRIC POTENTIAL CHARACTERISTICS FOR MAGNETOSPHERIC FLUX TUBES

by

J. LEMAIRE and M. SCHERER

ABSTRACT

The field aligned current density (J_{tot}) is a non-linear function of the applied potential difference (φ) between the ionosphere and the magnetosphere. This non-linear function has been calculated for plasma boundary conditions typical in a dayside cusp magnetic flux tube. The J - φ characteristic of such a flux tube changes when the temperatures of the warm magnetospheric electrons and of the cold ionospheric electrons are modified (see respectively figs. 2,3 and figs. 5,6); it changes also when the relative density of the warm plasma is modified (see fig. 4); the presence of trapped secondary electrons changes also the J - φ characteristic. The partial currents contributed by the warm and cold electrons, and by warm and cold ions are illustrated in fig. 1.

The dynamic characteristic of an electric circuit depends on the static characteristic of each component of the system: i.e. the resistive ionosphere, the return current region, and the region of particle precipitation whose field aligned current/voltage characteristics have been studied in this article.

RESUME

La densité du courant aligné (J_{tot}) dans le champ est une fonction non-linéaire de la différence potentielle (φ) appliquée entre l'ionosphère et la magnétosphère. Cette fonction non-linéaire a été calculée pour les conditions limites du plasma dans un tube de flux magnétique. La courbe caractéristique (J - φ) pour un tel tube de force magnétique varie lorsque les températures des électrons magnétosphériques chauds et des électrons ionosphériques froids sont modifiées (cf. figures 2, 3 et 5, 6). Elle varie également lorsque la densité relative du plasma chaud est modifiée (cf. fig. 4). La présence des électrons secondaires piégés est une autre cause de modification de la caractéristique (J - φ). Les courants partiels transportés par les électrons chauds et froids, ainsi que par les ions chauds et froids sont illustrés par la fig. n° 1.

La caractéristique dynamique d'un circuit électrique dépend du caractère statique de chacun de ses composants : c.-à-d. de la résistance de l'ionosphère, de la région des courants de retour et de la région de précipitation de particules dont les caractéristiques ont été étudiées dans cet article.

SAMENVATTING

De totale stroomsnelheid (J) evenwijdig aan het magneetveld is een niet-lineaire functie van het potentiaalverschil (φ) tussen de ionosfeer en de magnetosfeer. Deze niet-lineaire functie werd berekend voor typische randvoorwaarden voor het plasma in het CUSP-gebied langs de dagzijde. De karakteristieke curve (J - φ) in dit gebied is afhankelijk van de temperatuur van de warme magnetosferische elektronen en de koude ionosferische elektronen (zie figuren 2, 3 en 5, 6); zij verandert nog wanneer de relatieve dichtheid van het warme plasma gewijzigd wordt (zie figuur 4). De aanwezigheid van gevangen secundaire elektronen beïnvloedt ook nog de (J - φ) karakteristiek. De partiële stromen te wijten aan de warme en de koude elektronen, en aan de warme en de koude ionen worden in figuur 1 geïllustreerd.

De dynamische karakteristiek van een elektrische stroomkring is afhankelijk van de statische karakteristiek van elk bestanddeel van het systeem; d.i. van de weerstand van de ionosfeer, van het gebied van de terugkeerstromen, en van het gebied waarin deeltjes precipiteren en waarvoor de karakteristieken in dit artikel bestudeerd werden.

ZUSAMMENFASSUNG

Die Dichtigkeit von dem ausgerichteten Strom (J_{tot}) im Feld, ist eine nicht-lineare Funktion der potentiellen Differenz (φ), angewendet zwischen der Ionosphäre und der Magnetosphäre. Diese nichtlineare Funktion wurde berechnet für die Limitbedingungen von dem Plasma in einer Tube von magnetischem Fluss. Die Charakteristik (J - φ) für einer dergleichen Tube von magnetischer Kraft ändert wenn die Temperaturen von den warmen magnetosphärischen Elektronen und den kalten ionosphärischen Elektronen ändert werden (cf. Figuren 2, 3 und 5, 6). Sie ändert auch wenn die relative Dichtigkeit von dem warmen Plasma ändert wird (cf. Figur 4). Auch die Anwesenheit von eingeschlossen sekundären Elektronen ist eine Ursache der die Charakteristik (J - φ) ändern tut. Die partiellen Strömen, durch die kalten und warmen Elektronen, und auch durch die kalten und warmen Ionen gefördert, sind illustriert in der Figur 1.

Die dynamische Charakteristik eines elektrischen Stromkreis ist abhängig von dem statischen Charakter von den Bestandteilen : mit anderen Worten, von dem Widerstand von der Ionosphäre, von dem Rückstromgebiet und von der Niederschlagszone von Partikeln wovon man die Charakteristiken in diesem Artikel bestudiert hat.

1. INTRODUCTION

Dayside cusp magnetic flux tubes can be compared to diodes : the positively charged ionosphere is the anode, while the reservoir of warm magnetosheath particles is the cathode of the system. Like many types of electric components, such magnetospheric flux tubes have non-linear, (i.e. non-ohmic) current versus potential characteristics (see e.g. Knight [1973], and Lemaire and Scherer [1974], Fridman and Lemaire, 1980). These static characteristics of the magnetospheric system depend on the temperatures and densities of the collisionless electrons and ions spiralling along the magnetic field lines. Fridman and Lemaire [1980] studied the partial current carried by precipitated auroral electrons. This partial current is dominant for field aligned potential differences larger than 50-100 Volts. For smaller values of this potential difference between the ionosphere and the magnetosphere, the cold electrons and ions escaping from the topside ionosphere contribute a large fraction of the total field aligned current density. The scope of this article is more general, than our previous work since it addresses also the cases when the escaping ionospheric electrons carry almost all the return current density, when the potential differences are small.

2. THE KINETIC MODEL CALCULATION

Consider a high-latitude magnetic flux tube extending from the ionosphere (where the magnetic field intensity is B_1) up into the "plasma boundary layer" near the equatorial magnetopause. Along such a flux tube, magnetosheath plasma is injected from time to time (Carlson and Torbert, 1980). After a transient, corresponding to the propagation time of impulsively injected ions down to the ionosphere, the magnetosheath electrons and ions are mixed with the cold plasma of ionospheric origin consisting mainly of electrons, oxygen ions and hydrogen ions.

It will be assumed that a quasi-stationary field-aligned potential drop can develop between the low altitude reference level and the high altitude equatorial region where the magnetic field intensity B_M is reduced by a factor equal to the mirror ratio $a = B_M/B_I$.

For each species in the ion-exosphere it is possible to define a distribution function (e.g. a truncated Maxwellian) which has the same first order moments as the actual velocity distribution. For the magnetosheath particles this Maxwellian (characterized by two parameters N and E related respectively to the density and the temperature at the reference level), is truncated so that there is no return flux in the upward loss cone. Indeed, it is assumed that each particle with a mirror point below the reference level is lost by collisions. On the other hand, particles which are magnetically reflected above this level, do not contribute to the net parallel flux, and a fortiori they do not contribute to the total field aligned electric current density. Therefore, only magnetosheath electrons with pitch angles in the downward loss cone yield a positive upward current density. At the altitude of the reference level this current density is given by (Lemaire and Scherer, 1971)

$$J_{W.e} = e N_{W.e} \left(\frac{E_{W.e}}{2\pi m_e} \right)^{1/2} a^{-1} \exp \left[\frac{m_e \phi_g - e\varphi}{E_{W.e}} \right] \left\{ 1 + (a-1) \exp \left[\frac{a}{a-1} \frac{m_e \phi_g - e\varphi}{E_{W.e}} \right] \right\} \quad (1)$$

where φ is the total electrostatic potential difference along the magnetic field line, e is the electric charge, m_e the electron mass, and ϕ_g is the gravitational potential which can generally be neglected for electrons. The subscript w.e stands for "warm electrons".

The magnetosheath protons, injected downward into the magnetic flux tube yield, at the reference level, a current density given by :

$$J_p = -e N_p \left(\frac{E}{2\pi m_p} \right)^{1/2} \quad \text{for } e\phi > -m_p \phi_g \quad (2)$$

The flux of these protons is small and does not contribute significantly to the total current density defined by :

$$J_{\text{tot.}} = J_{w.e} + J_p + J_{H^+} + J_{O^+} + J_{c.e} \quad (3)$$

The small parallel electric field resulting from the gravitational charge separation of the cold ionospheric electrons (c.e) and the heavy oxygen ions accelerates the hydrogen ions outwards and decelerates the ionospheric electrons. As in the polar wind, the light hydrogen ions emerge from the ionosphere with a supersonic velocity and receive an additional acceleration through the large field aligned potential drop. Their contribution to the current density is given by

$$J_{H^+} = e N_{H^+} \left(\frac{E_{H^+}}{2\pi m_{H^+}} \right)^{1/2} \quad \text{for } e\phi > -m_{H^+} \phi_g \quad (4)$$

and by

$$J_{H^+} = e N_{H^+} \left(\frac{E_{H^+}}{2\pi m_{H^+}} \right)^{1/2} a^{-1} \exp \left[\frac{m_H \phi_g + e\phi}{E_{H^+}} \right] \left\{ 1 + (a-1) \exp \left[\frac{a}{1-a} \frac{m_H \phi_g + e\phi}{E_{H^+}} \right] \right\} \quad (5)$$

for $e\phi \leq -m_{H^+} \phi_g$

The partial current carried by the upward flowing electrons is given by :

$$J_{c.e} = -e N_{c.e} \left(\frac{E_{c.e}}{2\pi m_e} \right)^{1/2} a^{-1} \exp \left[\frac{m_e \phi_g - e\phi}{E_{c.e}} \right] \left\{ 1 + (a-1) \exp \left[\frac{a}{1-a} \frac{m_e \phi_g - e\phi}{E_{c.e}} \right] \right\} \quad (6)$$

When $e\phi$ is much larger than the thermal energy of the cold ionospheric electrons, the deceleration is important, and the escape flux is small. However, when e is smaller than or of the order of $E_{c.e}$, this flux becomes dominant.

The oxygen ions are also accelerated outwards. However, at the altitude of the parallel electric field acceleration their density is generally so small that their net upward flux is negligible. Therefore, J_{O+} will be ignored in the following calculations.

3. NUMERICAL STUDY OF THE FIELD ALIGNED CURRENT DENSITY

The relative importance of the different partial parallel current densities as a function of the total electrostatic potential difference along the magnetic field line in an ion-exosphere populated by cold electrons, oxygen and hydrogen ions, warm electrons and protons is illustrated in Fig. 1. The boundary conditions at the reference level, chosen at 1000 km, are summarized in Table 1.

As in the case of non-ohmic conductors, the total electric current density J_{tot} is a non-linear function of the field aligned electrostatic potential. When ϕ is much larger than $\frac{1}{e} E_{c.e}$ however, J_{tot} is a linear function of ϕ . This property is clearly illustrated in Fig. 1 where the solid curve representing J_{tot} is a straight line for $\phi > 5$ Volts. Fridman and Lemaire (1980) have already shown that the partial current carried by the warm electrons is a linear function of ϕ when $e\phi < E_{w.e}/a$. For magnetosheath electrons, $E_{w.e}$ is equal to 60 eV (i.e. 10 times smaller than for plasmashet electrons precipitating in auroral arcs), and therefore the linearity of $J_{w.e}$ (and consequently of J_{tot}) breaks down for $e\phi > \frac{B_I}{B_M} \cdot E_{w.e} \approx 60$ keV.

Note that the ohmic like behaviour of auroral field aligned currents was discovered experimentally by Lyons, Evans and Lundin (1979) and has been observed many times since.

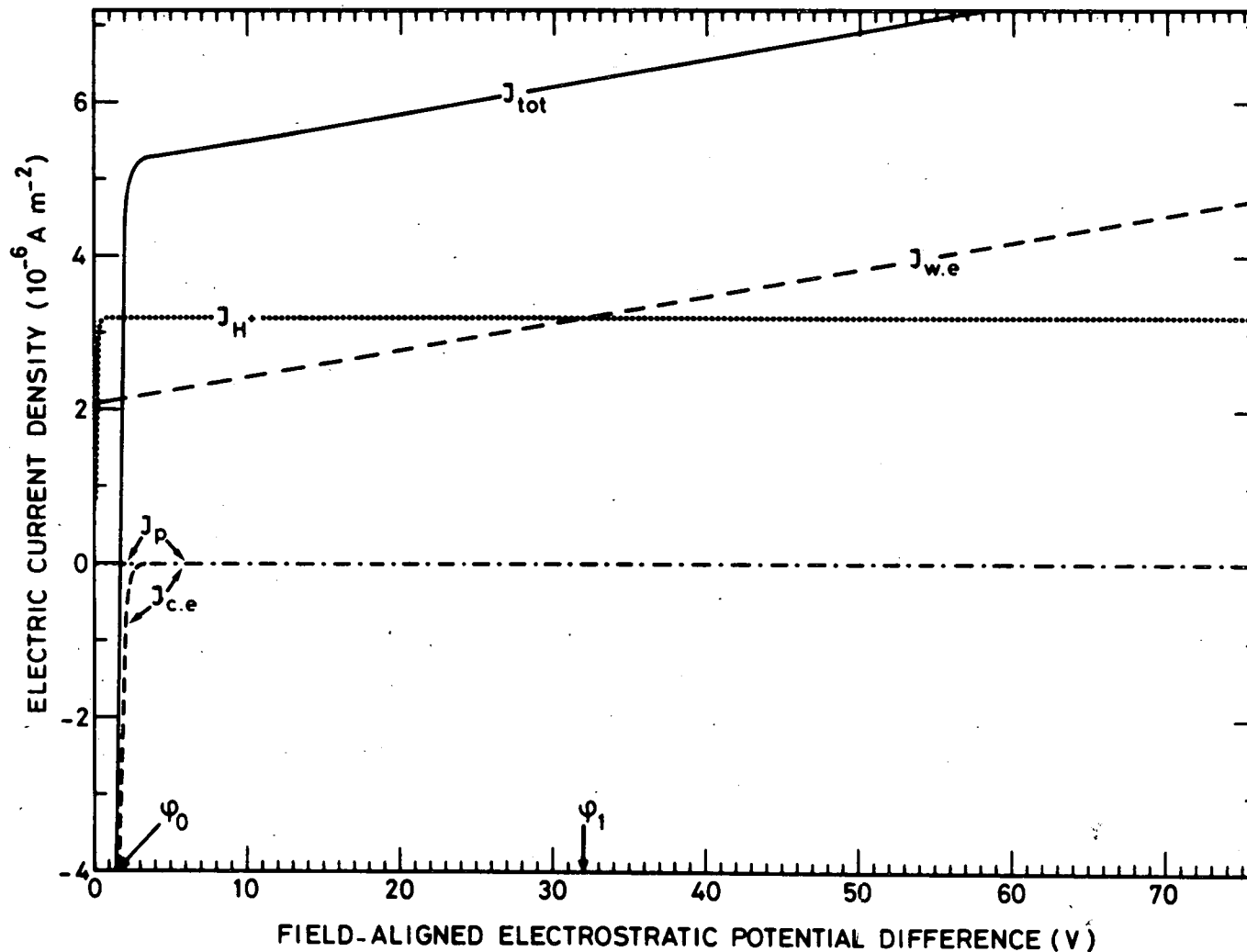


Fig. 1.- Partial and total field aligned currents in a dayside cusp magnetic flux tube as a function of the applied field aligned potential difference between the ionosphere and magnetosheath like plasma cloud. Plasma densities and temperatures used as boundary conditions are summarized in Table 1.

TABLE 1. Parameters for the Standard Model

Average energy (E_j), temperature (T_j) and number densities (n_j) of cold ionospheric electrons and ions at 1000 km altitude, of warm magnetosheath electrons and protons at high altitude.

j	c.e ⁻	O ⁺	H ⁺	s.e ⁻	w.e ⁻	p	
E_j	0.258	0.129	0.258	40	60.3	293	eV
T_j	3000	1500	3000	4.5×10^5	7×10^5	34×10^5	K
n_j	25000	2000	5000	0	10	10	cm ⁻³
$F_j (=0)$	$+4.3 \times 10^{11}$	-	$+ 4 \times 10^8$	0	-1.3×10^9	-6.7×10^7	cm ⁻²

F_j is the flux for each constituent when the electric potential difference (ϕ) is forced to be equal to zero. The parameters N_j are related to j the actual number densities (n_j) by normalisation factors described elsewhere (Lemaire and Scherer, 1971).

At small values of the partial current J_{H^+} is larger than $J_{w.e}$. The cross-over potential φ_1 , where $J_{H^+} = J_{w.e}$, can easily be obtained from eqs (1) and (4). For the boundary conditions given in Table 1, one obtains $\varphi_1 = 32$ Volt. On the other hand, there exists just one value φ_0 of the electrostatic potential, for which the total field aligned current vanishes. In the model considered here, this value is : $\varphi_0 = 1.6$ Volt.

When φ tends to φ_0 , the downward current carried by the escaping ionospheric electrons balances the upward current which is mainly due to outward flowing H^+ ions. The early hydrodynamic and kinetic polar wind model were based on the assumption that the net field aligned current was zero (Banks and Holzer, 1969, Lemaire and Scherer, 1970). This condition was used explicitly by Lemaire and Scherer (1970, 1973) to determine the field aligned potential difference along open magnetic field lines.

In the present model the sharp decrease of J_{tot} in the vicinity of φ_0 is due to the high sensitivity of $J_{c.e}$ to the small change of the electrostatic potential barrier that the ionospheric electrons with energies between 0.1 and 1.0 eV have to overcome in order to escape. The current which is transported by the cold electrons of ionospheric origin is illustrated by the dashed curve in fig. 1.

Fig. 2 shows the total current density J_{tot} versus the applied potential difference for three different velocity distributions of the warm electrons corresponding to $T_{w.e} = 14 \times 10^5$ K; 7×10^5 K and 3.5×10^5 K (i.e. $E_{w.e} = 120$ eV; 60 eV and 30 eV, respectively). The static characteristics plotted in fig. 2, for magnetospheric cusp field lines are similar to those deduced earlier by Lemaire and Scherer (1974) for the nightside auroral field lines. The extension of these characteristics into the negative current domain is shown in Fig. 3. When the electrostatic potential becomes smaller than φ_0 , the potential

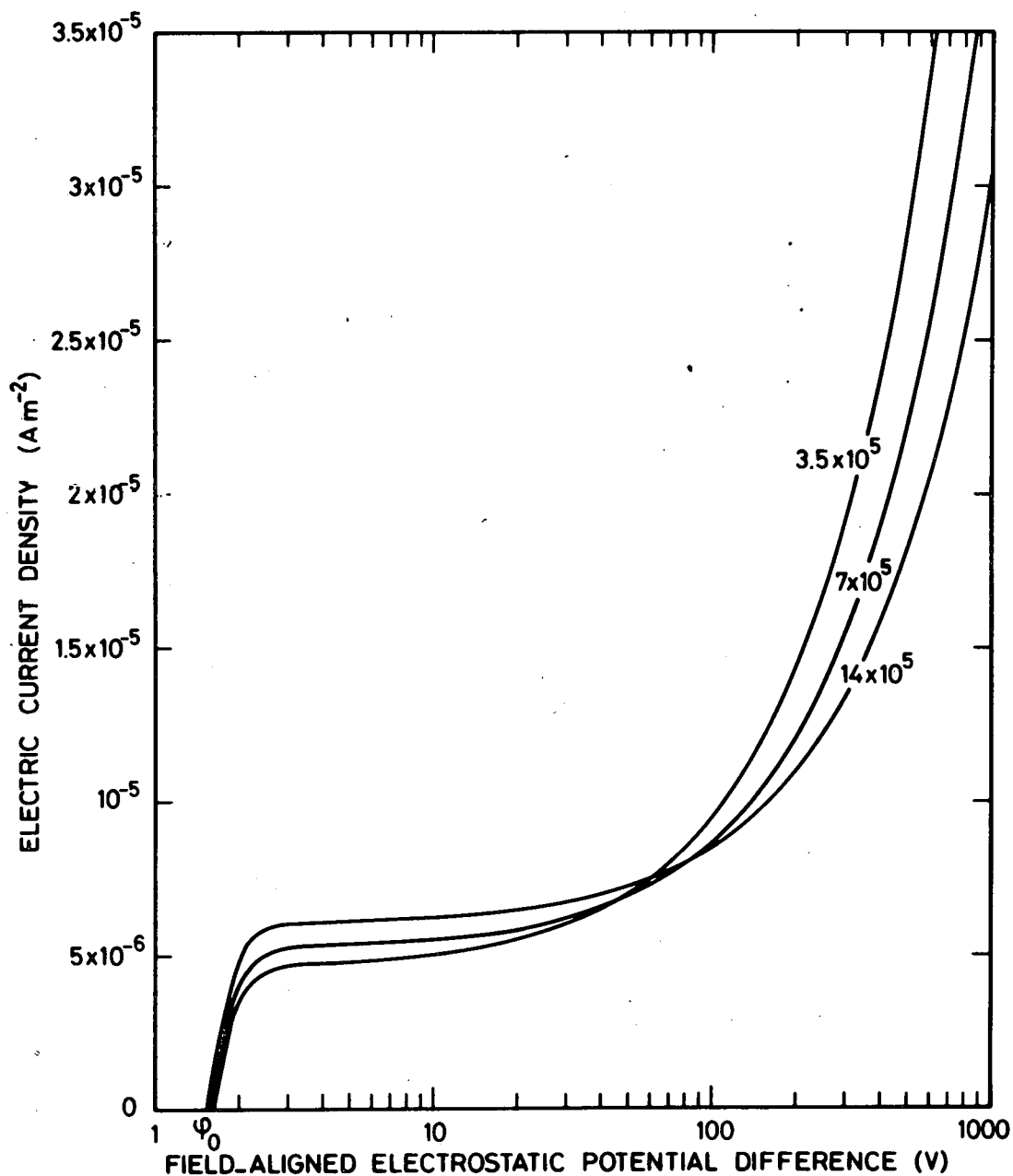


Fig. 2.- Influence of a change in the temperature ($T_{w.e} = 3.5 \times 10^5$; 7×10^5 ; 14×10^5 K) of warm magnetospheric electrons on the $J_{tot}-\phi$ characteristic of a dayside cusp magnetic flux tube. The other number densities and temperatures are summarized in Table 1. Note the non linearity of the characteristics except in a limited range of the potential difference.

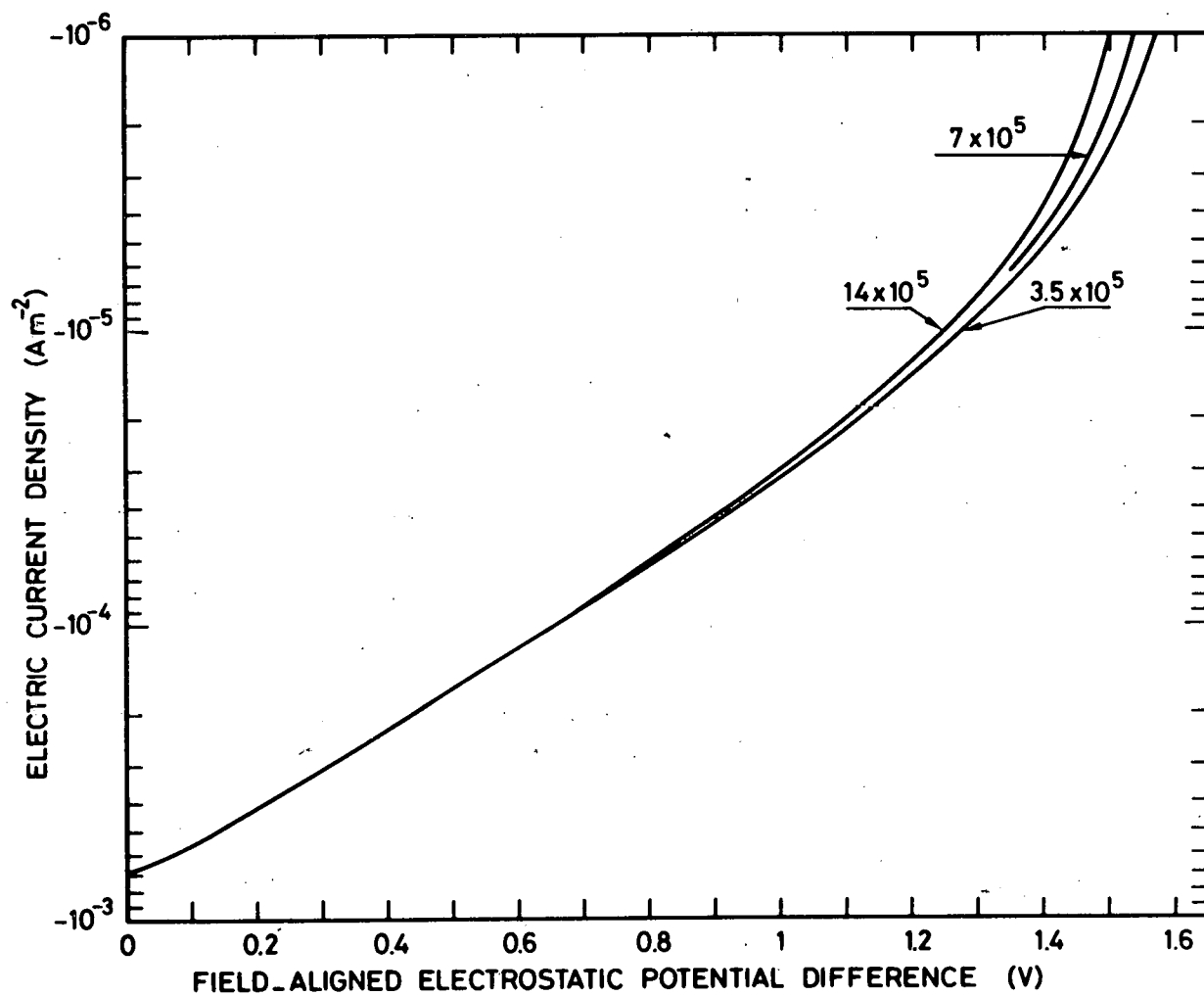


Fig. 3.- Extension of the characteristic curves of fig. 2, for field aligned potential differences smaller than 1.6 Volt. Note the large negative (return) current densities obtained at small values of the potential difference.

barrier for the cold ionospheric electrons is reduced and their escape flux is drastically enhanced. For small field aligned electrostatic potential differences (0.5 eV) the current carried by the cold electrons, is at least two orders of magnitude greater than the partial currents carried by the other constituents.

For a vanishing electrostatic potential, the escape flux of the ionospheric electrons is given by the Jeans evaporation flux formula for neutral particles of mass m_e , flowing out of the Earth's gravitational field. Hence the maximum for the electron escape flux is approximately given by

$$(F_{c.e})_{\max} = N_{c.e} \left(\frac{E_{c.e}}{2\pi m} \right)^{1/2} \quad (7)$$

Applying the boundary conditions in Table 1 yields a downward current of -0.7 mA/m^2 . Field aligned currents of such a large density have never been observed in the magnetosphere. Moreover, since $\mu_0 \mathbf{J} = (\text{curl } \mathbf{B})$, such a large parallel currents would cause an angular change in the magnetic field direction, greater than 1.5° per km in the direction of \vec{B} . This is almost two orders of magnitude greater than the normally observed spatial changes of the magnetic declination angles at 1000 km altitude. As a consequence it can be concluded that actual field aligned electron fluxes are always much smaller than the Jeans escape flux (7) and that is never equal to zero or negative.

Outside the areas where warm magnetospheric electrons are accelerated and precipitated into the atmosphere, the return currents transport cold thermal ionospheric electrons out of the ionosphere. It is clear from figs. 1 and 3, that a slight reduction of the electrostatic potential below ϕ_0 is enough to drag out of the ionosphere the large return current required to close the magnetosphere-ionosphere electric circuit.

In regions where negative return currents flow downwards i.e. for $\varphi < \varphi_0$, the Ohmic form of the $(J - \varphi)$ characteristic is no longer valid. Indeed, from fig. 3, it can be seen that the absolute value of the current increases when the potential decreases. This is clearly in contradiction with Ohm's law according to which the total current is directly proportional to the electrostatic potential.

Furthermore, it is not necessary to assume, as in the models of Chiu et al. (1981), that the field aligned potential difference changes sign when the electric current reverses direction at the frontier of the precipitation region and the return current area. The extension of the characteristic curves into the negative potential domain, would give much too large return current densities as can be deduced from fig. 3. Indeed, if the potential became negative (i.e. if the ionosphere were at a negative potential with respect to the magnetosphere) all the thermal electrons of the ionosphere would be accelerated out of the ionosphere, and all the ions would be precipitated. This process mechanism would build up an inversely directed charge-separation electric field opposing the applied negative field aligned potential.

In fig. 4 the $(J - \varphi)$ characteristics are plotted for 4 different densities of the magnetosheath particles i.e. : 5 cm^{-3} , 10 cm^{-3} , 20 cm^{-3} and 50 cm^{-3} . Since, $J_{w.e}$ is directly proportional to the magnetosheath electron density, the total parallel electric current is enhanced when the warm electron density is increased.

Figure 5 illustrates the influence of an increase of the temperature of the ionospheric electrons corresponding to an increase of the parameter $T_{c.e}$ from 2000 K to 6000 K. A larger average thermal velocity of the cold electrons enhances their escape flux. A larger potential φ_0 , corresponding to the zero-current condition, is then needed to reduce $J_{c.e}$ so that it becomes comparable to the current carried by the upward accelerated cold ionospheric ions. On the contrary, when the temperature of the hydrogen ions increases, the value of φ_0 is de-

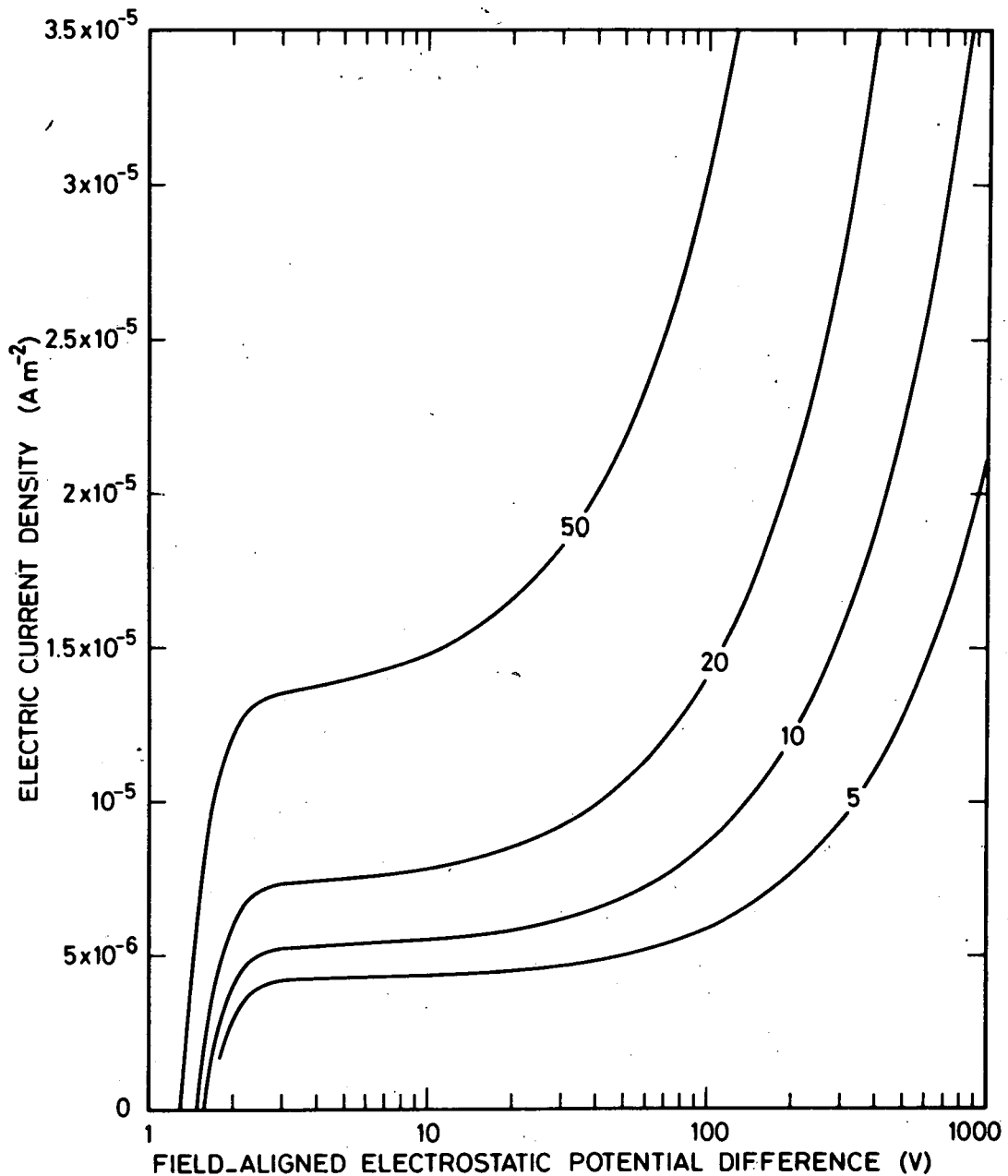


Fig. 4.- Influence of a change in the number density ($n_{w.e}$ and $n_p = 5; 10; 20; 50 \text{ cm}^{-3}$) of the warm magnetosheath plasma on the J - ϕ characteristic of a dayside cusp magnetic flux tube. The other number densities and temperatures are summarized in Table 1. Note the enhancement of J_{tot} , the total current (J_{tot}) resulting from the increased precipitation flux of warm electrons.

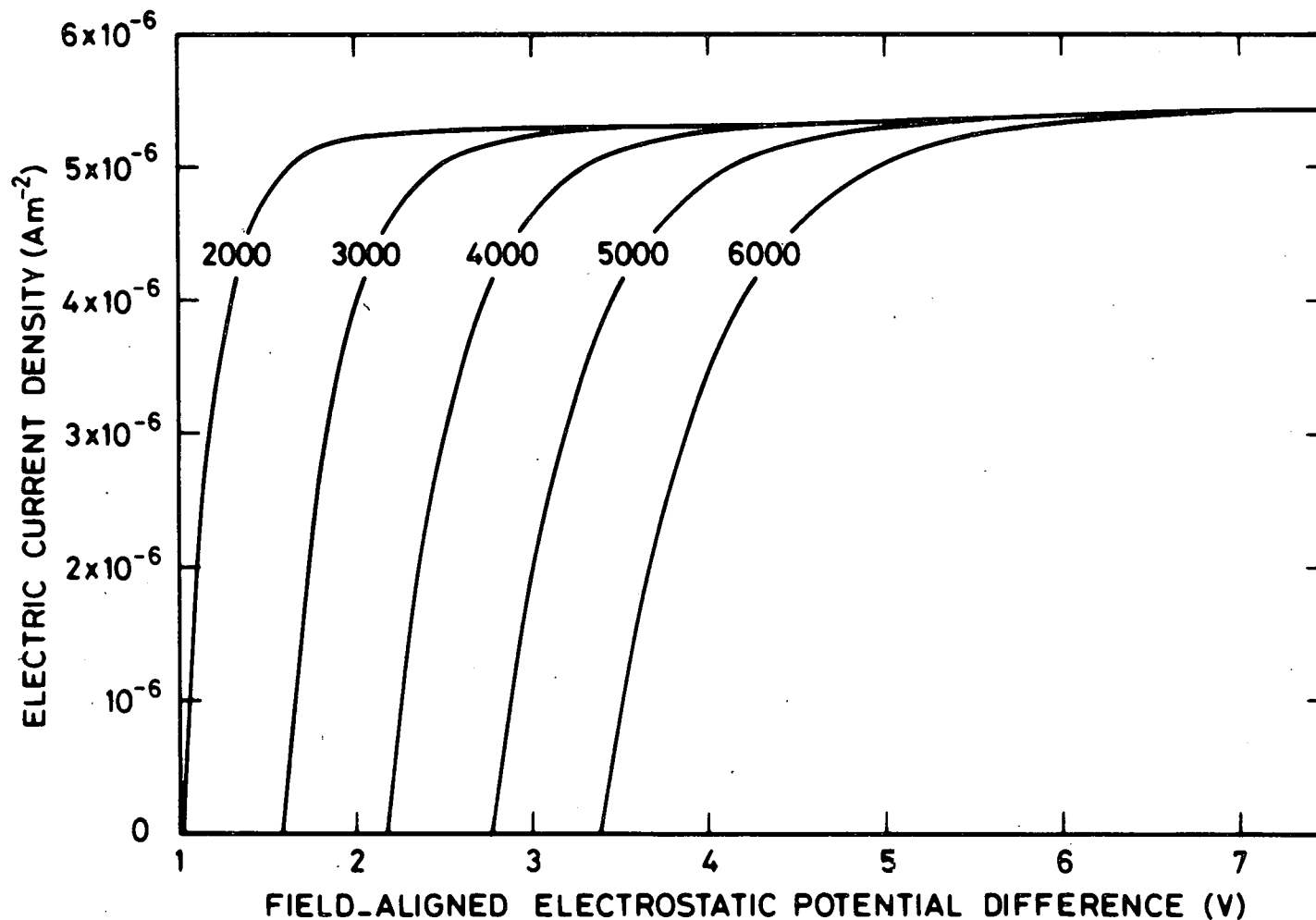


Fig. 5.- Influence of a change in the cold electron temperature ($T_{c,e} = 2000$; 3000; 4000; 5000; 6000 K) on the J- characteristic of a dayside cusp magnetic flux tube. The other number densities and temperatures are the same as for the standard model (see Table 1). Note that the value of the field aligned potential for which the total current vanishes, increases when the temperature of the ionospheric electrons is increased.

creased slightly. This is shown in Fig. 6 for the parameter values $T_{H^+} = 1500 \text{ K}$, 3000 K and 6000 K .

The $(J - \varphi)$ characteristic of open magnetospheric flux tubes can also be modified by the fluxes of the heavier ions, such as He^{++} , present in the magnetosheath plasma, or O^+ which is the major constituent in the ion-exosphere below $2000 - 3000 \text{ km}$ altitude.

The value of $J_{\text{He}^{++}}$ is always a small fraction of J_p , and J_{O^+} is generally much smaller than J_{H^+} . However, when the height of the electrostatic shock is below $2000 - 3000 \text{ km}$, the number of O^+ ions which are accelerated can exceed the flux of the H^+ ions, but both ionospheric ion-fluxes remain negligible compared to the partial current carried by magnetosheath electrons impulsively injected in the dayside cleft ionosphere.

The $(J - \varphi)$ characteristics of open magnetospheric flux tubes can also be modified by the presence of secondary electrons in the zone of particle precipitation. To evaluate the effect of these backscattered electrons, we assumed that they escape with a Maxwellian velocity distribution - the downward loss cone being empty - and that they have lost half of the kinetic energy they had before penetrating into the atmosphere. The net downward current ($J_{s,e}$) transported by these backscattered secondary electrons can then be calculated by means of eq. (6) where $E_{c,e}$ is replaced by $E_{s,e}$ and $N_{c,e}$ by $N_{s,e}$. In fig. 7 the dashed characteristic has been obtained by assuming that $N_{s,e} = 0$, and therefore $J_{s,e} = 0$; the solid curve shows the total field aligned current (including $J_{s,e}$) when $N_{s,e} = 5 \text{ cm}^{-3}$, $E_{s,e} = 40 \text{ eV}$, the other boundary conditions being the same as those of Table 1. The addition of a population of secondary electrons reduces the total upward current density.

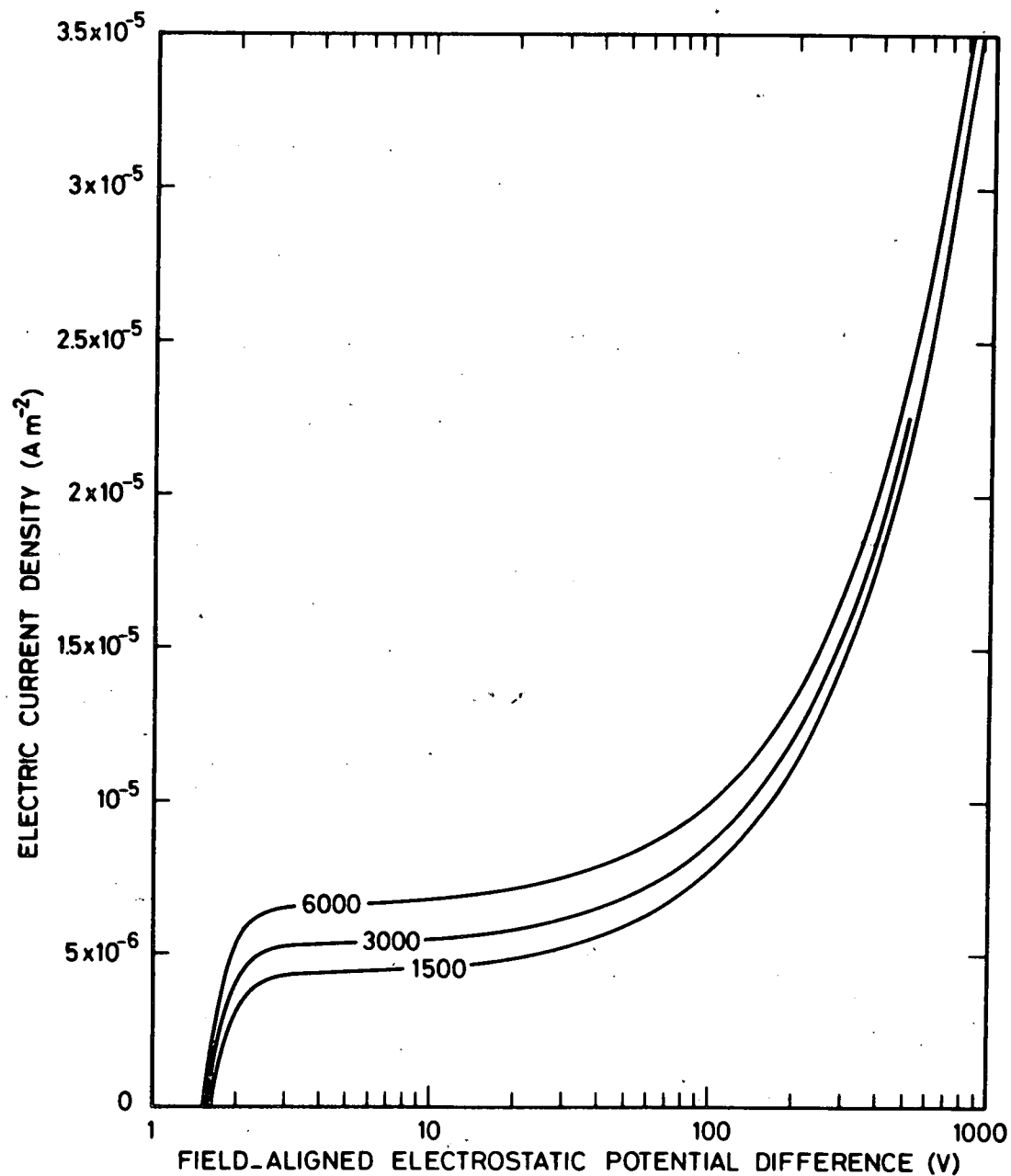


Fig. 6.- Extension of the (J_{tot}) characteristics of fig. 5, for higher values of the field aligned potential φ . Note the increase of the total upward current when the partial (down ward) current carried by the ionospheric electrons is enhanced with $T_{c.e}$.

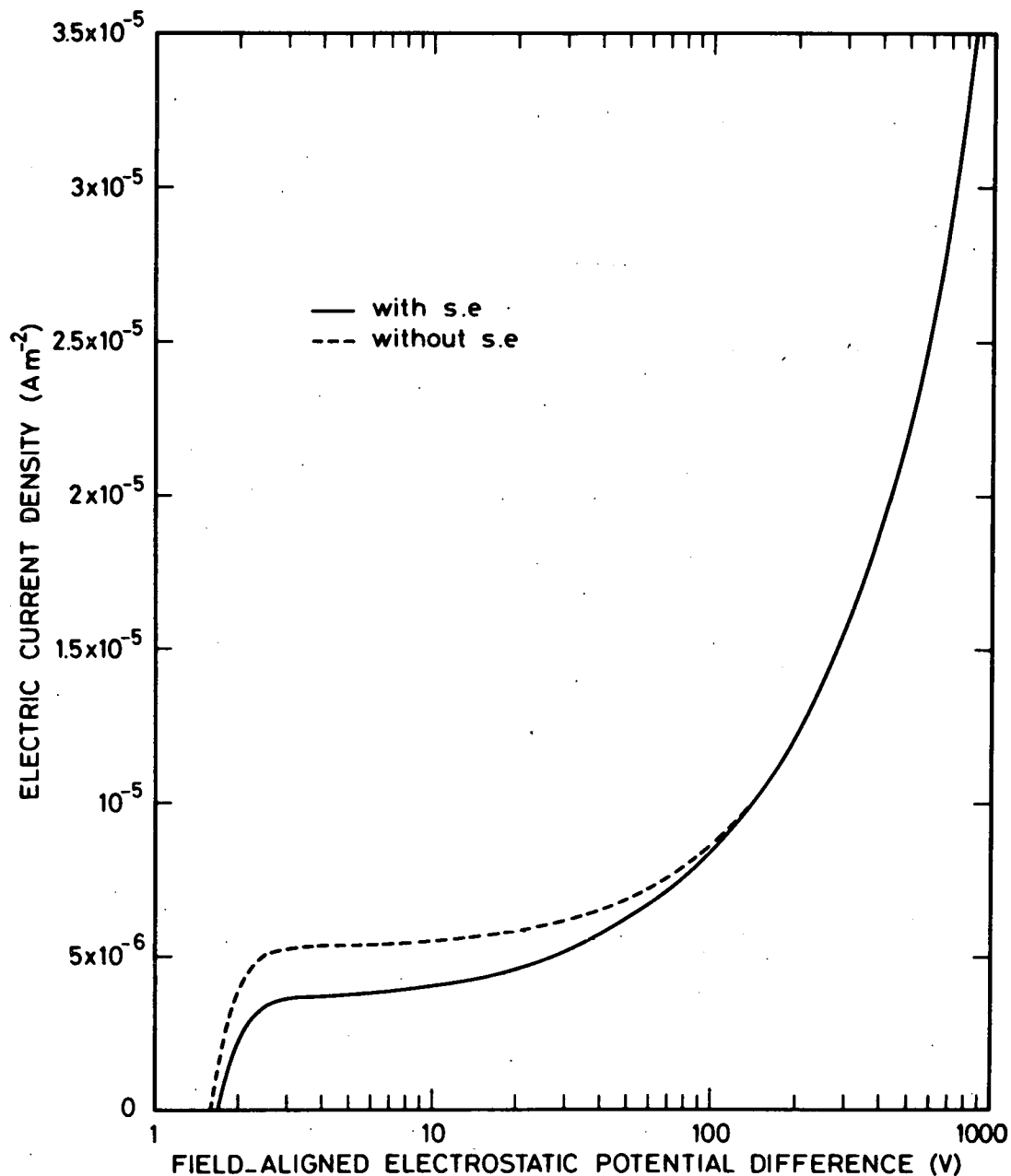


Fig. 7.- Effect of secondary electrons on the J - ϕ characteristics of a dayside magnetic flux tube. The dashed line corresponds to the standard model in which non secondary electrons were taken into account. The solid line illustrates the results when secondary electrons of 40 eV average energy are assumed to have a density of $n_{s.e} = 5 \text{ cm}^{-3}$ at the 1000 km. Note that the presence of escaping secondary electrons reduces the total upward current for values of the potential difference which are not much larger than the average energy of these additional outflowing electrons.

4. DISCUSSION AND CONCLUSIONS

Stationary solutions fail to be quasi-neutral when the field aligned potential exceeds a critical value (see e.g. : Stern, 1981). When ϕ exceeds this critical value, there is a multiplicity of different solutions corresponding to the same boundary conditions. The system is then probably unstable, and can jump or oscillate from one solution to another. Not all these solutions are quasi-neutral. The partial and total electric current densities are the same, however, since the boundary conditions in the ionosphere remain unchanged. Therefore, the characteristic curves described above are appropriate even when the parallel electric field becomes non-stationary in the electrostatic shock region. A non-stationary electric potential distribution is likely to develop electrostatic turbulence in the region of oscillating shocks or double layers. Magnetospheric electrons can be scattered while they traverse the acceleration region as a result of interaction with the electrostatic waves generated at the shock. It is generally assumed that the magnetic moment of the electrons and ions is conserved during the traversal of the narrow region where they are accelerated by a large parallel electric field. Nevertheless this can fail to be true when the electrostatic waves have a large amplitude in the direction normal to the magnetic field direction. In this case the perpendicular energy of the traversing particles may be modified, and their magnetic moment will then be changed non-adiabatically. As a result of this non-adiabatic pitch angle scattering, the net flux of precipitated magnetospheric electrons will be reduced. Indeed, strong wave particle interactions reduce $J_{w.e}$ (i) by scattering particles into the upward directed loss cone which has been assumed empty in the present calculations and (ii) by increasing the small pitch angles of precipitating electrons so that they become trapped.

The effects of wave-particle interactions, or of the contribution of J_{O+} to the field aligned fluxes, are corrections which still have to be worked out quantitatively. Nevertheless, the values of the fluxes

deduced within the framework of an ideal collisionless kinetic theory are adequate zero order approximations, good enough to facilitate a grasp of the basic physical processes involved, and appropriate to illustrate the effect of a change in the boundary conditions in the ionosphere or in the magnetosphere.

A magnetic flux tube in which currents flow out of the ionosphere into a hot magnetospheric plasma cloud constitutes a non-ohmic component of a global circuit. The DC potential generator is at high altitude, the load is the ionosphere where the transverse Pedersen currents flow horizontally through a resistive medium. The return current flowing outside the precipitation region forms another non-ohmic part of the magnetosphere-ionosphere electric system. This circuit has dynamic characteristics which differ from the static characteristics discussed in the present paper.

The perpendicular electric fields produced by the magnetospheric generator (e.g. the $\vec{V} \times \vec{B}$ field of a moving plasma cloud, or the charge separation electric field between two plasma regions of different temperature) are due to potential differences (φ_M) between adjacent magnetic field lines; φ_M is equal to the sum of (i) the field aligned potential in the precipitation zone (φ), (ii) the potential drop along field lines in the return current area ($\varphi' \approx 1 - 1.5$ Volt), and (iii) the ionospheric potential difference between these field lines (φ_I). The net field aligned current J_{tot} increases when φ_M increases. The curve $J_{tot}(\varphi_M)$ is the dynamic characteristic of the system. But since φ_M is not equal to φ , this dynamic characteristic of the circuit differs from $J_{tot}(\varphi)$, the static characteristic corresponding to one isolated flux tube which is only one single component of the global magnetosphere-ionosphere circuit.

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