Journal of Atmospheric and Terrestrial Physics, Vol. 40, pp. 337–342. Pergamon Press, 1978. Printed in Northern Ireland

Field aligned distribution of plasma mantle and ionospheric plasmas

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Abstract—The density and bulk velocity distributions of warm magnetosheath particles and cold ionospheric O^+ and H^+ ions are calculated along a polar cusp (cleft) magnetic field line. The warm collisionless plasma is injected at 12 earth radii, and interacts with the cold polar wind electrons and ions of ionospheric origin. After magnetic reflections in the exosphere (above 1400 km altitude) most of the ions move upwards along tail magnetic field lines and feed the plasma mantle flow. The bulk velocity of these warm protons is approximately 200 km s^{-1} and happens to be proportional to the average thermal speed of the magnetosheath ions at their injection point in the magnetosphere. The density in the plasma mantle is found to be about half that in the entry layer. The electric potential distribution is deduced from the quasi-neutrality condition, A large parallel electric field corresponding to an electrostatic double layer is obtained for the assumed boundary conditions.

Six years ago, when we published our kinetic model for the polar ion-exosphere, we did not realize that the same kinetic approach would also apply rather well to describe the preciptation of magnetosheath particles into the cusp, and that it could be used to model the tailward flow recently observed in the plasma mantle. In this short paper we will not give a mathematical formulation of our standard kinetic model, but we will only discuss the numerical results obtained for one model calculation corresponding to reasonable boundary conditions at the exobase and entry layer. For those interested in a detailed description of the kinetic model we refer to some of our earlier papers (Lemaire and Scherer, 1971, 1972).

Figure 1 shows a meridional section of polar cusp flux tubes along which entry layer particles flow down on the equatorial side, and where plasma mantle particles flow up on the poleward side. Moreover, the flux tubes are filled from below with cold plasma of ionospheric origin. This cold plasma consists mainly of oxygen and hydrogen ions and cold electrons, for which the densities and energies at the exobase level (1400 km) are summarized in Fig. 1. The number densities have been taken from ISIS II measurements (Hoffman *et al.*, 1974) at an altitude of 1400 km in the polar cusp which is very close to the level at which the Coulomb collisions between ionospheric particles become negligible. The energies at the exobase are conservative guesses corresponding to reasonable ionospheric temperatures. Finally, the flow velocities at the exobase are calculated from the first order moments of a truncated Maxwell–Boltzmann distribution which is empty in the downward loss cone.

The magnetosheath electrons and protons are assumed to be injected at high altitudes with isotropic pitch angles except in the upward loss cone. At the exobase the densities of these warm particles (subscript w) have been chosen to obtain, near the magnetopause, a number density of 10 particles per cm^3 for either electrons or protons, and electron and proton temperatures of 10^6 K and 7×10^6 K respectively. Finally we also give in Fig. 1 the number densities n and flow velocities V in the entry layer at 69,000 km, and in the plasma mantle at an altitude of 45,000 km.

Above the exobase level the collisionless particles interact only through a charge separation electric field. This field can be derived from an electrostatic potential which must be a solution of Poisson's equation. Solving Poisson's equation along a magnetic field line is a very difficult problem which fortunately can be avoided whenever the electrostatic potential can be determined satisfactorily by imposing local charge neutrality at each altitude. Using this method we calculated the electric potential for the boundary conditions illustrated in Fig. 1, and for a difference of 25 V between the exobase and the magnetopause region. The results are plotted in Fig. 2. The shaded region below 1400 km is the collision-dominated region where the exopheric solutions are not valid. To extend the kinetic solution downwards into the lower ionosphere a hydrodynamic approach can be used (Lemaire, 1972; Lemaire and Scherer, 1975). As can be seen from Fig. 2, the electrostatic potential decreases monotonically from 25 V at the exobase to almost zero at the magnetopause. At about 19,000 km there exists a rather sharp potential drop, or double-layer. At this altitude the corresponding

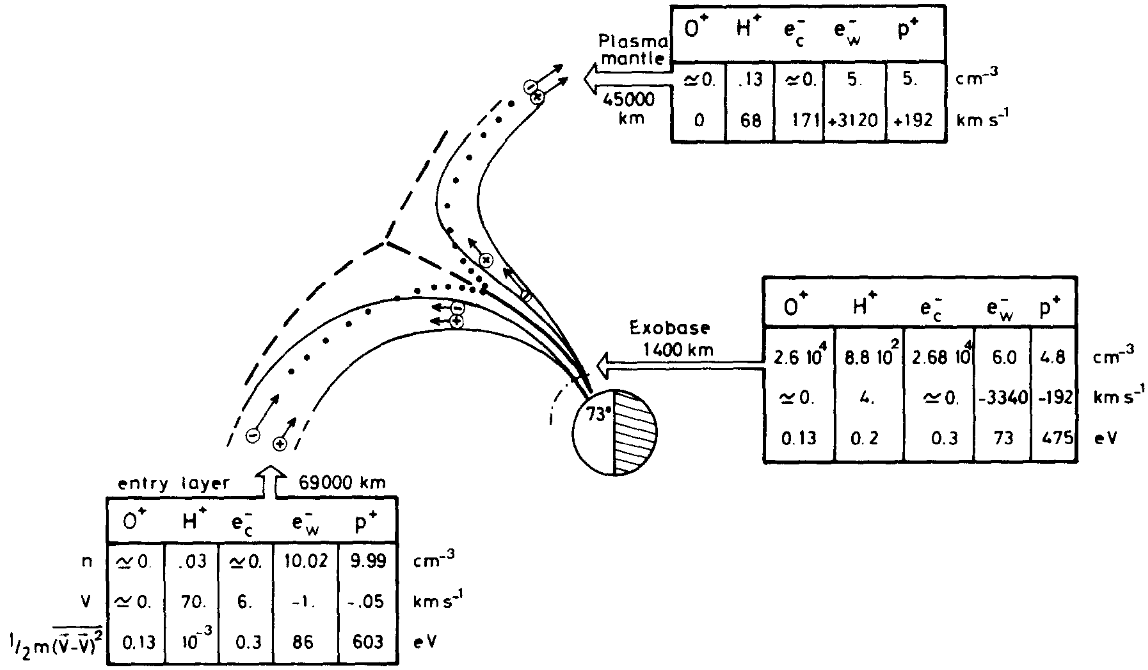

Fig. 1. Meridional section of polar cusp flux tubes with assumed boundary conditions for the present model calculation. The first lines in the inserted tables give the densities (n) of cold Oxygen (O^+), Hydrogen ions (H^+), cold electrons (e_c), warm electrons (e_w), and warm protons (p^+) of magnetosheath origin. The second lines correspond to the bulk speeds (V) of these particles (positive values of V mean upward flow velocities). The third lines in the tables correspond to the mean thermal energy $\frac{1}{2}m\overline{(\mathbf{v}-\mathbf{V})^2}$ or kinetic temperature, in eV, for each of the charged particles considered.

parallel electric field, determined from the slope of the potential curve and shown in Fig. 3, has a peak intensity of 0.1 V/m (out of the frame of this figure). The thickness of this potential jump is approximately 50 m which is about twice the local Debye length. Since in our one-dimensional model the double layer is perpendicular to the magnetic field, this result could be expected from the discussion of electrostatic shock waves by KAN (1975). For the more general case of an oblique double-layer the thickness will probably be of the order of several ion gyroradii (SWIFT, 1975).

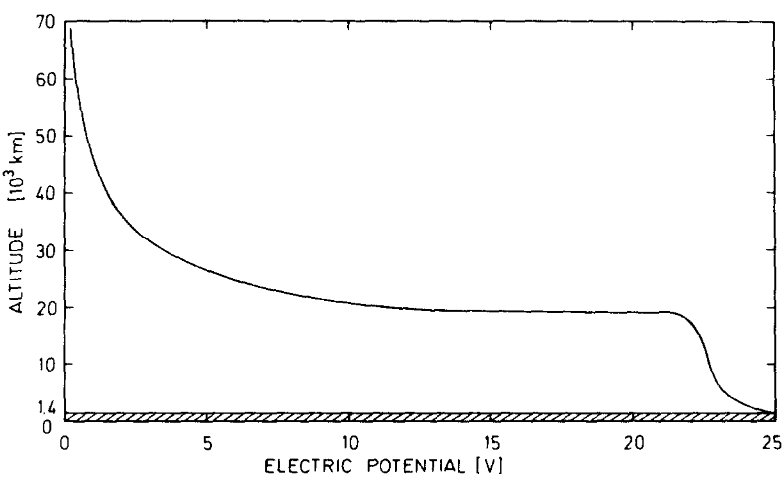

Fig. 2. Electrostatic potential distribution in the collisionfree region.

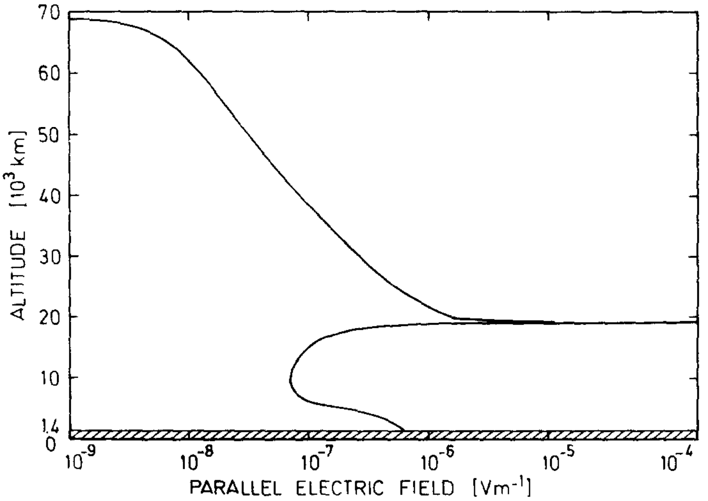

Fig. 3. Parallel electric field distribution in the collisionfree region. The maximum value of 0.1 V m^{-1} reached at the double layer is out of the frame of this figure.

The density distributions of the different constituents are illustrated in Fig. 4. The number density of the oxygen ions, which is dominant at the exobase rapidly decreases with a scale height of 500 km. At 4500 km, the hydrogen ions (H^+) become predominant, and finally at 13,000 km the warm protons (p^+) become the major ion species. Across the double-layer the ionospheric hydrogen density decreases sharply as a consequence of the impulsive acceleration of these escaping ions. The sudden acceleration is clearly illustrated in Fig 5, where the flow velocities of the different kinds of particles are plotted. Once they have passed the double layer, the ionospheric hydrogen ions form a field aligned and almost mono-energetic stream moving upward with a flow speed of 70 km s^{-1}. The number density of the electrons of ionospheric origin has a very sharp decrease at the double-layer. This is due to the fact that almost all low energy electrons are reflected by the 25 Volt electrostatic potential barrier, and therefore the cold electrons form a cushion of trapped particles on which the double layer rests. The escape flux of these ionospheric electrons is also very small as a consequence of the high potential barrier, and the flow velocity near the exobase is almost zero.

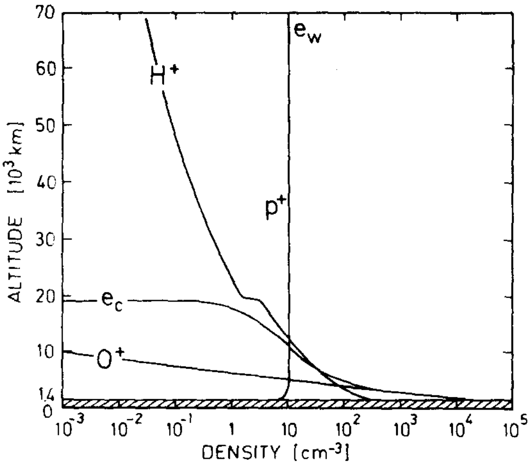

Fig. 4. Number density distributions in the collisionfree region.

The flow velocity of the warm protons is directed downwards in the entry layer and is only 50 ms^{-1} at the equator. This low velocity results from the small number of precipitating particles compared with those which are injected with a pitch angle outside the narrow loss cone. However, when the altitude decreases the loss cone opens, and the flow velocity of the warm particles increases proportionally to the magnetic field intensity. At the top of the ionosphere the precipitating protons have reached a downward flow speed of 200 km s^{-1}. This apparent acceleration is only a consequence of the convergence of the magnetic field lines. Magnetosheath alpha particles which are injected with a temperature 4 times larger than the warm proton temperature will have nearly the same flow velocity as the protons (cf. Table 1). These calculated alpha and proton flow velocities are consistent with recent observations made at 800 km by SHELLEY *et al.* (1976) and are also supported by the

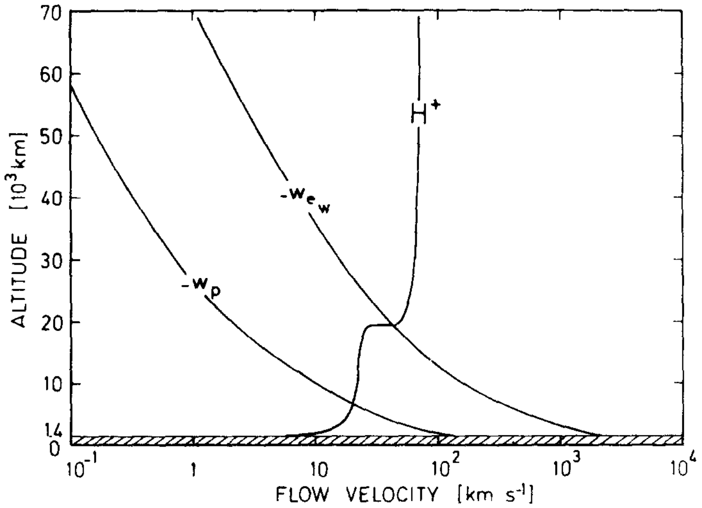

Fig. 5. Flow velocities in the collisionfree region, calculated under the assumption that particles reflected above the exobase do not contribute to the net flux.

observations in the entry layer (PASCHMANN *et al.*, 1976).

The number densities of the warm protons and electrons are also plotted in Fig. 4. They do not vary much with altitude and they are almost equal. When plotted using a linear density scale (Fig. 6), differences of density are evident. At altitudes lower than the electrostatic double layer the number density of the warm electrons exceeds the warm proton number density by 2–3 particles/cm^3. Above the double layer this difference is much smaller and tends to negligibly small values at high altitudes.

The flow velocity of the warm electrons exhibits a similar behaviour to the flow speed of the magnetosheath protons, but is much larger in absolute value. These precipitating electrons of magnetosheath origin carry the largest fraction of the field aligned electric current. This is illustrated in Table 1, where the different fractional parallel currents corresponding to each kind of particles are given at the exobase level. The results summarized in the table were obtained for similar boundary conditions to those discussed here, but with the additional presence of a small quantity of ionospheric helium ions and precipitating α-particles. The values of the parallel current densities are given in the last column: positive values correspond to upward currents, negative values to downward currents. The warm magnetosheath electrons transport 90% of the total upward directed electric current. The largest mass flux, however, is carried by the escaping ionospheric hydrogen ions (see Table 1, column 4).

Finally, plotted in Fig. 7 are the (downward directed) flow velocities of the warm protons and

Table 1. The fractional mass fluxes (4th column) and parallel electric current densities (last column) for each kind of particle (1st column) at the exobase level (1400 km). The densities (2nd column) and temperatures (3rd column) are also given. The potential difference between the exobase and the magnetopause region is assumed to be 25 V

j	n(cm^{-3})	T(K)	mnw(kg m^{-2} s^{-1})	$J_{\|}$(A m^{-2})
e_c	26914	3500	0	0
O+	2600	1500	0	0
H^+	880	3000	5.8×10^{-15}	5.6×10^{-7}
He^+	34	3000	4.5×10^{-16}	1.1×10^{-8}
e_w	6.5	10^6	-2.0×10^{-17}	3.5×10^{-6}
p^+	4.8	7×10^6	-1.5×10^{-15}	-1.5×10^{-7}
He^{++}	0.2	3×10^7	-2.6×10^{-16}	-1.3×10^{-8}
TOTAL	0	—	4.5×10^{-15}	3.9×10^{-6}

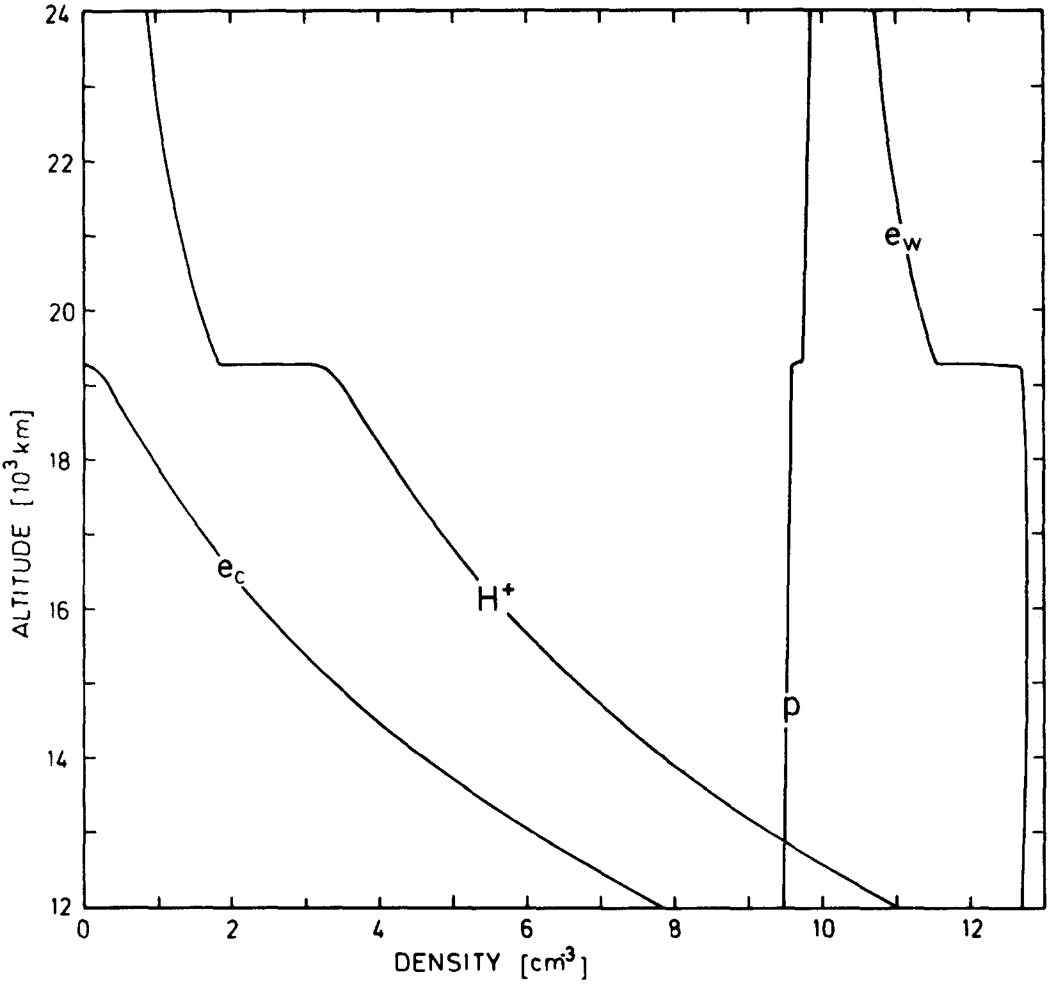

Fig. 6. Number density distribution in a part of the collisionfree region.

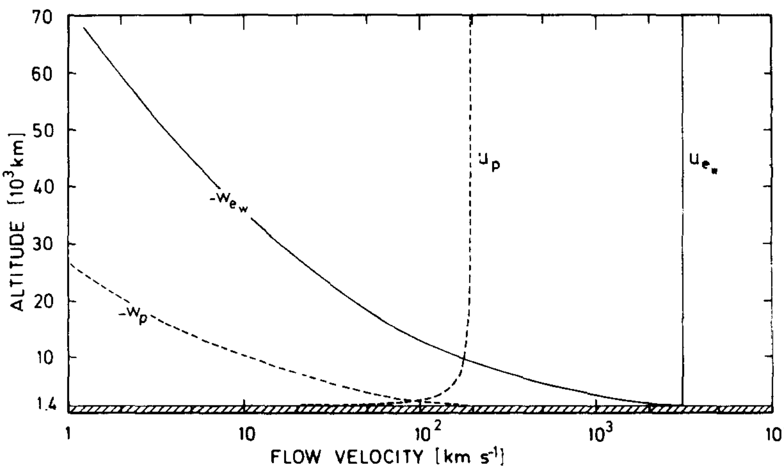

Fig. 7. Flow velocities in the collisionfree region: u_p and u_{e_w} are calculated under the assumption that the downward flux of the warm particles is zero in the plasma mantle.

electrons calculated under the assumption that particles reflected above the exobase do not contribute to the net flux in the entry layer. However, assuming with ROSENBAUER *et al.* (1975) that the plasma mantle is composed of magnetosheath particles which have been mirrored and have drifted polewards in the mid-altitude cusp region, we estimated the upward flow speed in the plasma mantle. This calculation showed that the tailward flow velocity of the magnetosheath protons (u_p in Fig. 7) is 200 km s^{-1}, which is approximately half the thermal speed at the injection point in the magnetosphere. Therefore, according to this model calculation it can be suggested that the ion flow velocity in the plasma mantle is proportional to the square root of the dayside magnetosheath proton temperature.

According to the present kinetic calculation the density in the plasma mantle is half that in the entry layer. The calculated density and flow velocity of the warm protons in the plasma mantle and entry layer seen to be in agreement with the observations (PASCHMANN and HAERENDEL, 1976; SCKOPKE and PASCHMANN, 1976).

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