IMPULSIVE PENETRATION OF SOLAR WIND PLASMA AND ITS EFFECTS ON THE UPPER ATMOSPHERE

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ABSTRACT

Impulsive Penetration of solar wind plasma irregularities transfers energy, momentum and particles into the magnetosphere. The effects on the upper atmosphere are examined and discussed. The heat deposition in the E-region (and above) due to Joule dissipation of depolarization currents is evaluated and compared to the energy production due to the absorption of solar radiation.
The wind speed imparted to ionospheric plasma in the throat region and over the polar cap is compared to the observed convection velocities. The impulsive injections of magnetosheath-like plasma observed at low altitudes in the dayside cusps are interpreted as consequences of field aligned expansions (spreadings) of engulfed solar wind filaments (intrusions) into the magnetosphere.

Keywords : Magnetopause, coupling of magnetosphere and upper atmosphere.

1. INTRODUCTION

An overwhelming amount of in situ observations made for more than 15 years near the ecliptic plane have indicated that the coronal expansion blows uninterruptedly ionised matter out of the Sun with a velocity (V) ranging from 320 km s^{-1} to 710 km s^{-1} at 1 A.U. The number density (N) of the solar wind protons varies between 3 cm^{-3} and 20 cm^{-3}. The electron temperature (T_e) fluctuates between 9 x 10^4K and 20 x 10^4K. The proton temperature (T_p) is sometimes smaller by a factor 5, sometimes larger by a factor of 3 than the electron temperature. The total flux of particles (NV) ranges between 1.5 x 10^8 cm^{-2} s^{-1} and 7.8 x 10^8 cm^{-2} s^{-1}. The flux of momentum density (mNV^2) varies even more : from 1 x 10^{-8} to 5.8 x 10^{-8} g cm^{-1} s^{-2} (Ref. 1).
For more than a decade the solar wind plasma has been supposed to be almost uniform and steady over distances comparable to the diameter of the magnetosphere. The interaction between this uniform and supersonic plasma flow and the geomagnetic field leads then to the formation of a smooth and symmetrical magnetopause surface where the normal component of the gas bulk velocity is zero. In front of this ideal surface is the Bow Shock where the solar wind speed jumps from its supersonic value to a subsonic regime. The outcome of steady state theories of the interaction between the solar wind and the geomagnetic field was an impressive series of interesting but controversial magnetospheric models : "closed" steady state models, and "open" magnetospheric models have had their advocates at all periods. It is not our purpose to repeat here neither the merits nor the limitations of both these models, indeed this has been explained in several reviews (refs. 2, 3 and 4). Let us just say that both of these alternative approaches have their own difficulties resulting from the oversimplification on which these steady state mathematical models are based. At first glance, it appears often convenient or easier to describe natural phenomena in the frame of static or stationnary models, but it happens often also that such over-simplifications must be abandoned later on. Indeed sometimes the physical processes involved in Nature are, by essence,non stationary. It is now more and more accepted that this must be the case for the interaction between the corpuscular radiation emitted by the Sun and our geomagnetic field environment. Recent high resolution magnetic field and plasma measurements confirm the older radioscintillations observations (Refs. 5 and 6) and show that the solar wind is formed of filamentary plasma irregularities. The density fluctuations convected passed a spacecraft or across a radioastronomical source can amount to $\Delta N/N \simeq 5$ - 10% over distances ranging from 300 km up to scales exceeding the dimension of the magnetosphere. Considering the solar wind as a bundle of interwinded small-scale irregularities with inhomogeneous momentum densities,it has recently been proposed that the penetration of solar wind plasma into the magnetosphere proceeds impulsively instead of beeing a steady state interaction process (Refs. 7 and 8). It is this impulsive entry mechanism that will be recalled briefly in the next section. The consequences for the magnetosphere - atmosphere system are finally discussed in section 3.

2. THE IMPULSIVE INJECTION

As for a gusty wind blowing at the surface or against the ocean, engulfment of air bubbles in the boundary layer depends on the spectrum of the momentum irregularities carried by the impinging wind. The larger the excess of momentum, the deeper the solar wind plasma irregularity will be able to penetrate into the magnetosphere. This has been schematically illustrated in Fig. 1. The hatched areas represent cross sections of filamentary solar wind plasma elements at different distances from the magnetopause. Consider one of these elements with a 5% excess density compared

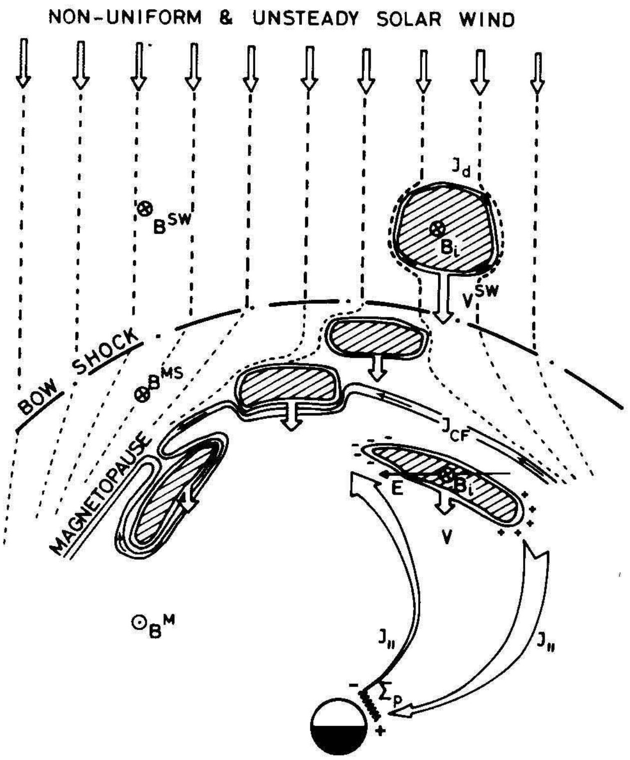

Fig. 1. Sequence of events representing the positions of a solar wind plasma irregularity penetrating through the Bow Shock and Magnetopause. $\underline{J}_d$ is the sum of magnetisation, grad-B, and curvature currents ; $\underline{J}_{CF}$ is the Chapman-Ferraro current density; $\underline{B}_i$, $\underline{B}^{SW}$, $\underline{B}^{MS}$, $\underline{B}^M$ are the magnetic field intensities inside the plasma elements, in the solar wind, in the magnetosheath and in the magnetosphere respectively; $\underline{E}$ is the polarisation electric field ($- \underline{V} \times \underline{B}_i$) induced in the magnetosphere by the plasma elements moving with the velocity $\underline{V}$; as soon as the plasma element is engulfed in a region with finite integrated Pedersen conductivity, the excess of kinetic energy of the intruding irregularity can be dissipated by Joule heating; the excess of momentum is transferred to the ionospheric plasma in the throat region.

to the background plasma ; when the bulk speed of this irregularity is equal to average solar wind speed its excess of momentum is also 5% higher than average momentum density. Once behind the bow shock the density inhomogeneity moves at a subsonic velocity with a higher velocity than the background magnetosheath plasma. This is a consequence of the conservation of momentum across the bow shock transition. The densities (N) and temperatures (T) of the plasma have increased both inside and outside the moving volume element in a manner approximately described by the Rankine-Hugoniot equations. The magnetic field intensity (B_i) and (S), the normal cross section of the filament, vary in order to conserve magnetic flux ($B_i S$). The element is compressed in the direction of the shock normal.
At the magnetopause where the average solar wind has a zero normal velocity component, the density inhomogeneity still has an excess of momentum. This implies a penetration velocity (V) of 20 km s^{-1} if the original solar wind velocity of this element was 400 km s^{-1}. As a consequence of conservation of mass and momentum the element dents in the magnetopause and moves across the geomagnetic field lines which are rooted into the conducting ionosphere of the Earth. The polarization current induced by the inertial force of the moving mass element carries polarization charges toward the east and west sides of the element as indicated in Fig. 1. An electric potential difference and an electric field

$$\underset{\sim}{E} = - \underset{\sim}{V} \times \underset{\sim}{B}_i \qquad (1)$$

builds up across the plasma element as shown in Fig. 1. The magnetic field lines crossing the edges of the plasma element link the polarization charges down into the dayside cusps ionosphere. The convection electric field $\underline{E}$ (measured in a fixed frame of reference !) maps also down to the low altitude E-region near 80° invariant latitude and 12 hours local time.
The Pedersen conductivity is high in this part of the upper atmosphere because of the large collision frequency of the ambiant ions with neutral particles. A transverse (horizontal) electric current flows in the direction of the applied ionospheric electric field. As a consequence of this Pedersen current, the polarization charges appearing at the sides of the plasma element are partially neutralized and the electric field $\underset{\sim}{E}$ is reduced (short circuited). A decrease of E (i.e. $/\dot{E}/ < 0$) implies a decreasing bulk velocity (i.e. $\dot{V} = \dot{E}/B < 0$). In other words the bulk speed of the plasma element does not remain constant as in the case when the integrated Pedersen conductivity (Σ_p) is zero or very small. Because of the finite value of ionospheric conductivity (Σ_p = 0.2 - 1 Siemens) the element is slowed down in a characteristic time ($\tau_2 \propto \Sigma_p^{-1}$) of the order of 10 minutes for the example considered above and taken from Ref. 7. In this time lapse a plasma element with a diameter of 10,000 km can move a distance of one Earth radius beyond the average magnetopause surface. The excess of kinetic energy carried by the intruding filament or plasma slab is dissipated into Joule heating in the ionosphere which is considered as the ohmic resistance in the equivalent electric

circuit illustrated in Fig. 2.
Besides this electro-mechanical interaction there is an electromagnetic interaction between the magnetized plasma element and the geomagnetic field. Indeed Lemaire et al. (Ref. 9) have shown that penetration and engulfment requires certain orientations for the magnetization vector $\underline{M}$ associated with a current carrying plasma element. The magnetization is determined by the local current density $\underline{J}$ = curl $\underline{M}$, while the external magnetic field $\underline{H} = \underline{B}/\mu_0 - \underline{M}$ is determined by the distant (non-local) current systems. The condition for easy penetration and even acceleration of the plasma element towards the inside of the magnetosphere is

$$\underline{M} \cdot (\underline{B}^{M} - \underline{B}^{MS}) > 0 \qquad (2)$$

where $\underline{B}^{MS}$ is the magnetosheath field and $\underline{B}^{M}$ is the magnetospheric field oriented Northwards near the equatorial plane; $\underline{B}^{M}$ is oriented in the sunwards direction for the northern magnetotail lobe and in the antisunwards direction for the southern lobe of the magnetosphere. A similar magnetic interaction and acceleration force is experienced by a small dipole magnet when it is approached close to another magnetic dipole whose magnetic moment is anti-parallel to the former one. If on the contrary the two magnetic moments are parallel to each other the equation (2) is not satisfied and the magnets repel each other. So will also do the geomagnetic field at the magnetopause for a plasma element with an unfavourably oriented magnetization $\underline{M}$.
An alternative way of viewing this interaction is via the $\underline{J} \times \underline{B}$ force which balances the pressure gradient force when plasmas and fields are in equilibrium. Considering the simplest case in the equatorial plane, the Chapman-Ferraro magnetopause currents ($\underline{J}_{CF}$) are from dawn to dusk (see Fig. 1). The diamagnetic currents ($\underline{J}_d$) circulating around a plasma pressure and density enhancement are counterclockwise when the magnetosheath field is Southwards ($B_z^{MS} < 0$) ; indeed in this case the magnetic field produced by the current system $\underline{J}_d$ must have a northward component in order to reduce the magnetic pressure inside the filament to keep the total pressure constant. When these diamagnetic currents at the leading plasma edge combine with the oppositely directed Chapman-Ferraro current, the net $(\underline{J}_d + \underline{J}_{CF}) \times \underline{B}$ force is suddenly reduced at the place where the filament impacts on the magnetopause surface. On the other hand, the plasma pressure gradient force at the leading edge of the plasma element is enhanced. As a consequence of the imbalance of forces acting on the boundary, the plasma irregularity is accelerated towards the inside of the magnetosphere. However, when the IMF or the field in the magnetosheath is northwards the $\underline{J}_d \times \underline{B}$ and $\underline{J}_{CF} \times \underline{B}$ forces add to each other to oppose the enhanced plasma pressure gradient force. (Ref. 9).
The presence of a moving plasma element does not only perturb the local electric field distribution, but it changes also the local magnetic field distribution in the magnetosphere and in the ionosphere (Ref. 7). The intrusion of solar wind filaments across the magnetopause modifies the magnetic field lines in the outer magnetosphere. Because of the finite Pedersen conductivity and via the field aligned (Birkeland) currents, the geomagnetic field lines can interconnect with those of the interplanetary magnetic field. Such a patchy "merging" process is not necessarily a consequence of in-situ dissipation processes (wave-particle interaction as in conventional merging theories). Indeed, it can also be based on diffusion of magnetic fields out of a magnetized plasma element as a result of classical collisions in the distant ionospheric regions (Ref. 10)

3. SOME CONSEQUENCES FOR THE MAGNETOSPHERE - ATMOSPHERE SYSTEM

As a consequence of Impulsive Penetration solar wind particles, momentum, and energy are transfered inside the magnetosphere and deposited in the atmosphere. In this section we will discuss these three points with more details.

3.1. Transfer of energy

In the previous section we have seen that the excess of kinetic energy carried by the impulsively injected plasma elements is partially dissipated into the lower ionosphere by Joule heating. The field aligned currents ($\underline{J}_{\parallel}$) are closed in the ionosphere by transverse Pedersen currents ($\underline{J}_{\perp}$) in the E-region near 115 km altitude where the collision frequency of ambiant NO^+ ions becomes equal to their gyrofrequency. Transverse diffusion of charges and Joule dissipation are expected in this part of atmosphere which is an ohmic load for the equivalent current system since $\underline{J}_{\perp} \cdot \underline{E}_I$ is positive. Note that the polarization currents ($\underline{J}_p$) in the plasma element itself is anti-parallel to $\underline{E}$, as any electric generator i.e. $\underline{J}_p \cdot \underline{E} < 0$ (Ref. 11). One can estimate the power dissipated in the atmosphere by an intruding solar wind plasma element with an excess momentum of 5%. As a consequence of conservation of momentum the penetration velocity (V) through the magnetopause is approximately 20 km s^{-1} i.e. 5% of the solar wind velocity before the bow shock. A typical value for the magnetic field inside of the filament is B_i = 30 nT. Consider the case when B_i has a southward component, the convection electric field given by eq. (1) has then a component in the y-direction i.e. from dawn to dusk. The intensity of E is 0.6 mV/m. When this electric field is mapped down into the dayside cusp ionosphere its intensity E_I is increased by a geometrical factor given by $2\,L^{3/2}\cos\alpha$, where L is the McIlwain parameter of the geomagnetic field lines interconnected with those of the engulfed filament ; α is the angle between $\underline{E}$ and the equatorial geomagnetic plane : $\cos\alpha = B_{i,z}/B_i$. For L = 10 and $\alpha = 30°$, E_I = 32 mV/m. This electric field drives Pedersen currents whose density is given by $J_{\perp} = \sigma_P E_I$. The power dissipation by Joule heating is $J_{\perp} . E_I = \sigma_P E_I^2$, σ_P is the ion Pedersen conductivity

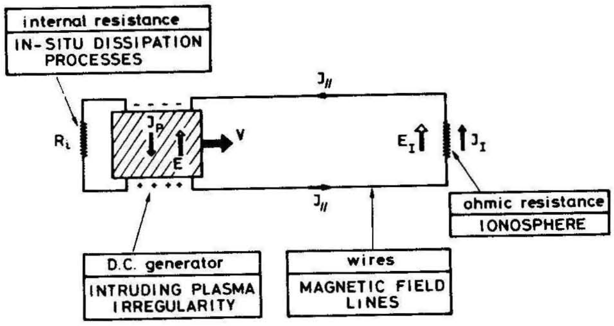

Figure 2. Equivalent electric current induced by a plasma element moving in the magnetosphere with a velocity $\underline{V}$ which is perpendicular to a magnetic field. The hatched area corresponds to the plasma element; $\underline{E}$ is the polarization electric field and $\underline{J}_P$ is the polarization current moving in a direction antiparallel to $\underline{E}$; the plasma element is a D.C. electric generator; the ionosphere is the load (ohmic resistance) where Pedersen currents ($\underline{J}_I$) close the current loop formed by Birkeland field aligned currents ($J_{\parallel}$); R_i is the internal resistance of the MHD generator resulting from local (in situ) wave - particle interactions.

$$\sigma_p = \frac{n_i e^2}{m_i \nu_{in}} \qquad (3)$$

ν_{in} is the ion-neutral collision frequency; σ_p is maximum where ν_{in} becomes equal to the ion gyrofrequency $\nu_L = 30\ s^{-1}$ (Ref. 12). This occurs between 115 km and 140 km where the NO^+ number density is of the order of $3 \times 10^4\ cm^{-3}$. From eq. (3) it can then be deduced that $(\sigma_p)_{max}$ = 5×10^{-4} mho/m. Furthermore, $J_{\perp} = (\sigma_p)_{max}\ E_I$ = $1.6 \times 10^{-5}\ A\ m^{-2}$ and $\underline{J}_{\perp}\underline{E}_I = 5.1 \times 10^{-7}$ W $m^{-3} = 5.1 \times 10^{-6}\ erg\ cm^{-3}\ s^{-1}$. This power dissipated per unit volume element compares well with the value calculated in Ref. 13 under other conditions. Note that $\underline{J}_{\perp}.E_I$ is a factor 5 larger than the heat deposited at the same altitudes by solar radiation (Ref. 14). Therefore it can be expected that Joule heating by intruding plasma elements increases significantly the temperature of the ions and neutral gas in the E-region below the dayside cusps. The energy dissipated there diffuses downwards by thermal conduction and is transported to other latitudes and longitudes by the wind systems of the upper atmosphere. Note however, that the Joule heating by an intruding solar wind irregularity is only confined in a relatively small volume of the upper atmosphere. Indeed the vertical extend of the region of dissipation is only one or two atmospheric scale height (i.e. 10 km). The horizontal cross section of the heated volume corresponds to the field aligned projection of the engulfed solar wind filament upon the ionosphere. For instance a plasma element of 10,000 km diameter near the magnetopause dissipates its excess of kinetic energy over an horizontal area of only 150 km latitudinal width. This Joule dissipation in the dayside cusps E-regions is a first example of interaction between the magnetosphere and the terrestrial atmosphere.

At higher altitudes where the Pedersen conductivity becomes smaller, dissipation of the field aligned currents can also be envisaged as a consequence of electron-ion Coulomb collisions. The parallel conductivity

$$\sigma_{\parallel} = \frac{n_e e^2}{m_e \nu_{ei}} \qquad (4)$$

is typically of the order of 10 mho/m at 300 km altitude in the F-region where $n_e = 10^6\ cm^{-3}$, T_e = 1000 K, and $\nu_{ei} = 1.5 \times 10^3\ s^{-1}$. The limiting field-aligned electric current density is $J_{\parallel} \simeq n_e e\ \overline{v}_i = 10^{-4}\ A\ m^{-2}$, where $\overline{v}_i$ is the ion thermal speed. Consequently, $E_{\parallel} \leq J_{\parallel}/\sigma_{\parallel} = 10^{-2}$ mV/m. The maximum Joule heating resulting from dissipation of such Birkeland currents by Coulomb collisions is equal to $J_{\parallel}.E_{\parallel} = 10^{-9}\ W\ m^3$ = $10^{-8}\ erg\ cm^{-3}\ s^{-1}$.

The minimum UV absorption (for $\lambda < 1026$ Å) is of the same order of magnitude in the 250-300 km range in low temperature atmospheric models (Ref. 14). To increase the efficiency of dissipation of field aligned currents the parallel conductivity should be reduced. Wave-particles interactions, triggered when the currents approach the limiting value and become instable, reduce $\sigma_{\parallel}$ below the value corresponding to Coulomb colliisions. The additional heat deposition due to ohmic or anomalous dissipation of electric currents at high altitudes increases the plasma temperature within the magnetic flux tube interconnected with the solar wind plasma irregularity. The formation of field aligned ionospheric irregularities can result from such a patchy and localized heating of the upper ionosphere. Alternative possibilities for the formation of small scale ionospheric irregularities have been proposed in Refs. 15, 16 and 17.

Observational evidence for heating of the ionospheric plasma up to 1000 km altitude, is shown in Fig. 3 taken from Titheridge (Ref. 18). The narrow temperature peak seen at high latitude (L = 20) is located below the dayside cusps. When the magnetic activity index is increased this temperature peak moves towards lower latitudes (L = 10). This corresponds to the equatorward motion of the neutral points when the magnetosphere is more heavily compressed by the solar wind i.e. when the solar wind plasma irregularities are stopped in the average at smaller radial distances (Ref. 19).

There is also evidence that the thermospheric temperature and densities are enhanced in the range of latitudes and local times corresponding to the dayside cusps (Ref. 20). The patchy and localized heating of the dayside cusps atmosphere may possibly modify the global wind circulation in the E-region and even deeper into the terrestrial atmosphere.

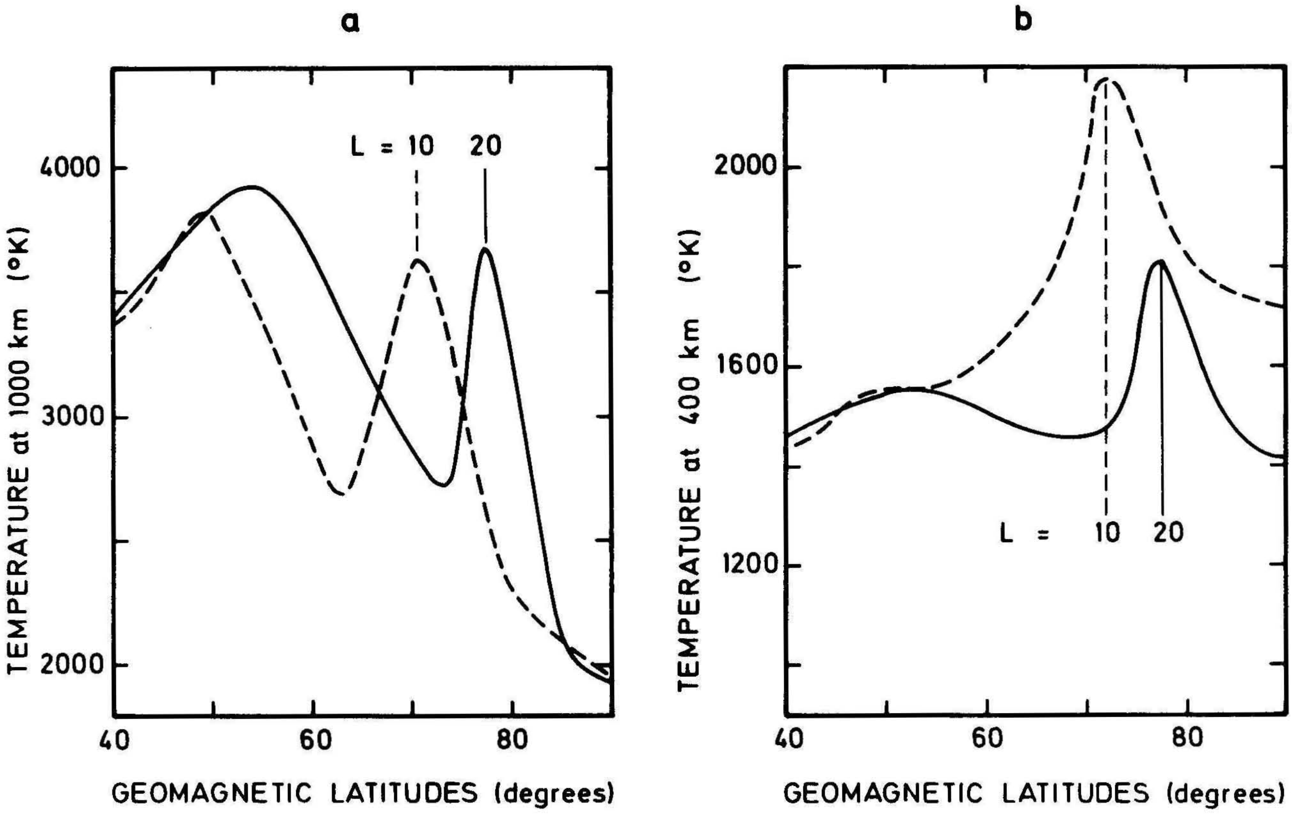

Figure 3. Average ionospheric temperatures as a function of geomagnetic latitudes during quiet geomagnetic conditions ($K_p \simeq 1.5$, solid curves) and during perturbed conditions ($K_p \simeq 4.5$, dashed curves). The narrow peaks at L = 10 (and L = 20) are located along the field lines of the dayside cusp. These localized temperature enhancements at 1000 km and 400 km altitude are due to dissipation of the excess kinetic energy carried by intruding solar wind irregularities (from Ref. 18).

3.2. Transfer of momentum

When a plasma irregularity moves across the geomagnetic field lines as discussed above, the convection electric field $\underline{E}$ map in the topside ionosphere. This electric field (E_I) imposes a drift motion to the ionospheric electrons and ions trapped in the magnetic tube of force interconnected with the intruding plasma element. For E_I = 32 mV/m and B_I = 0.5 10^{-4}T the ionospheric drift velocity, given by

$$\underline{V}_I = \frac{\underline{E}_I \times \underline{B}_I}{B_I^2} , \qquad (5)$$

is equal to 640 m s^{-1}. Since $\underline{E}$ and $\underline{E}_I$ are directed from dawn to dusk the low altitude convection velocity is directed towards the magnetic poles. Momentum is first transfered to the ionospheric plasma from the middle of the throats i.e. at the feet of the "last closed" field line tangent to the magnetopause. When the element proceedes inwards in the frontside magnetosphere, momentum is transfered at the feet of more equatorward field lines, i.e. at lower L-values in the noon local time sector. Repetitive actions of this kind can impart a general convection pattern from the throat region over the polar caps as illustrated in figure 4. (Ref. 21). The ionospheric convection velocities observed at 250 km altitude in the dayside cusps are 500 ms^{-1} - 2000 ms^{-1}, in agreement with the value calculated above for a typical solar wind irregularity intruding into the frontside magnetosphere.
At lower altitudes where the collision frequency between ionospheric particles becomes important the convected ions transfer their momentum to neutral atmospheric constituants and drag the neutral atmosphere over the polar caps. At 150 km altitude the characteristic time to transfer the horizontal momentum to the thermosphere and to impart a transpolar velocity of 500 ms^{-1} is only of the order of 1 hour (Ref. 13).

3.3. Transfer of solar wind particles

Impulsive penetration of solar wind irregularities as described above is not the only mechanism able to transfer momentum into the magnetosphere. Indeed hydromagnetic waves propagating at the surface of the magnetopause can also impart some momentum from the magnetosheath to the magnetospheric plasma and field (Ref. 22). However, it is difficult to see how such hydromagnetic waves could inject particles across the average magnetopause into the magnetosphere. That magnetosheath-like particles are present earthward from the magnetopause and at almost all latitudes and longitudes has been clearly demonstrated by in situ observations (Ref. 23 - 30 and 37).

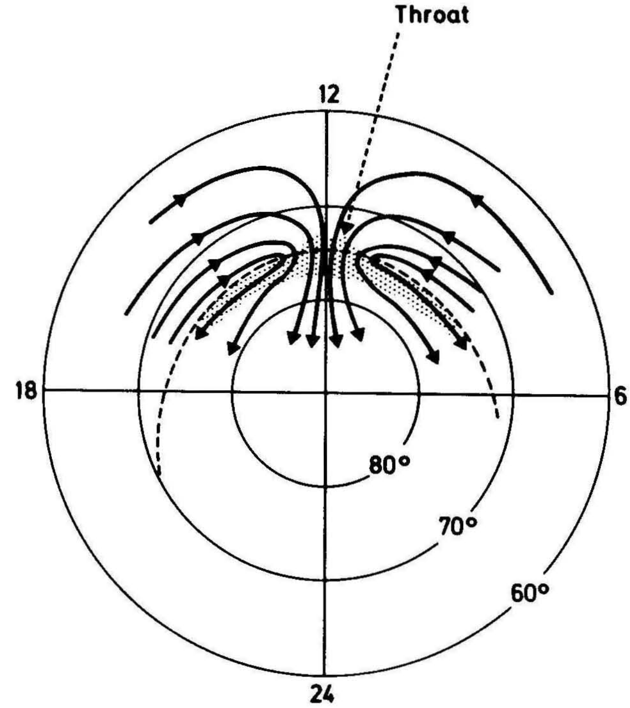

Figure 4. Schematic view of the dayside high-latitude ion flow pattern observed near 250 km altitude. Momentum is transfered to ionospheric plasma in the throat region (from Ref. 21).

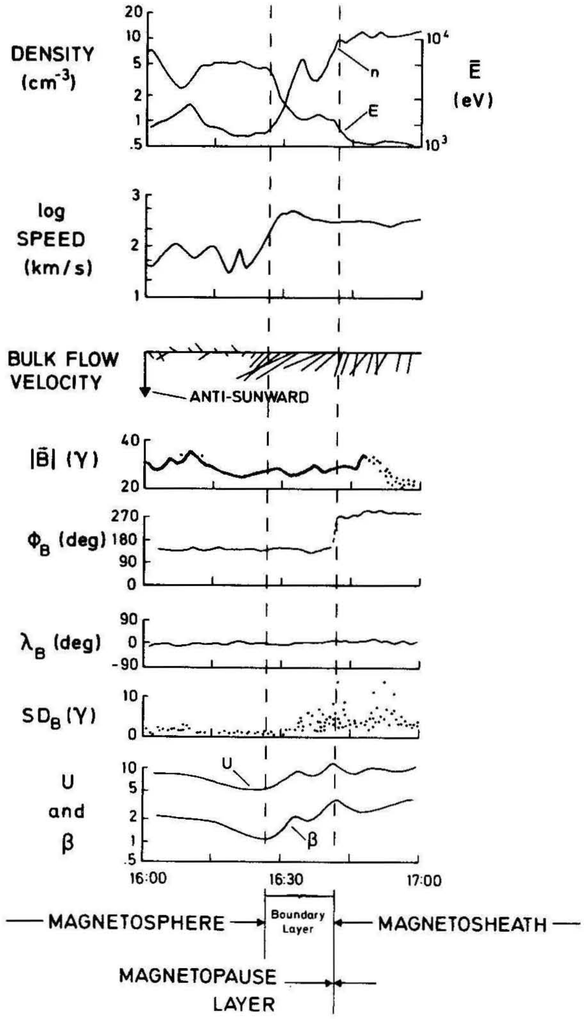

Figure 5. Basic characteristics of the Low Latitude Boundary Layer are illustrated. Various plasma regions are identified : U denotes the total energy density (in keV/cm^3). SD_B denotes the standard deviation of magnetic field fluctuations (in nT); B, ϕ_B, and λ_B are the average magnetic field intensity, latitude and longitude; the bulk flow velocity direction and magnitude are also shown; n and E are the plasma density (in cm^{-3}) and mean energy (in eV). (from Ref. 27).

An up to date review of observational evidence for the existence of a well defined Plasma Boundary Layer (PBL) earthward of the Magnetopause Layer has recently be given by Eastman and Hones (Ref. 27). Magnetosheath-like electrons and ions are seen in the PBL on closed geomagnetic field lines at the same time and at the same place as trapped magnetospheric electrons and ions. Figure 5 illustrates how the overall proton density and bulk flow velocity decrease from the magnetopause layer to the inner surface of the plasma boundary layer (going from right to left in figure 5) and are accompanied by an increase in thermal energy and continued magnetosheath-level low frequency magnetic field fluctuations, given by the standard deviation SD_B. The plasma β (ratio of plasma to magnetic field energy density) usually drops to values smaller than unity in the inner portion of the PBL, consistent with the decay of field fluctuations. Within the PBL the plasma flow directions are more variable and usually shift into a direction that is more nearly tangent to the average magnetopause surface than is the nearby magnetosheath flow direction (Ref. 27).

A theory of propagating hydromagnetic waves at the magnetopause surface as proposed in Ref. 22, nor steady state diffusion processes across the relatively thin magnetopause current layer as discussed in Ref.31,hardly can account for all the observations made in the PBL (see Ref. 19). Direct evidence of detached magnetosheath-like plasma intrusions into the magnetosphere have recently been obtained from ISEE observations (Ref. 27). These observations support impulsive penetration of solar wind irregularities with an excess of momentum.

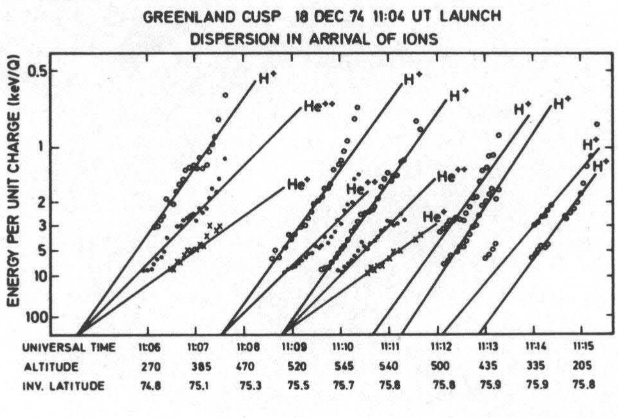

Figure 6. Dispersion curves of the inverse velocity (labelled by corresponding energy per charge) versus arrival times at low altitude corresponding to ion spectra peaks. The H^+ lines are the least squares fit to dominant peaks. The He^{++} and He^+ are theoretical dispersion curves with slopes $1/\sqrt{2}$ and $1/\sqrt{4}$ of the corresponding proton line. The injections times are at the intersection of the dispersion lines on the Universal Time axis. The slopes correspond to injection distance of 12 $\pm$ 1 Earth radii (Ref. 34).

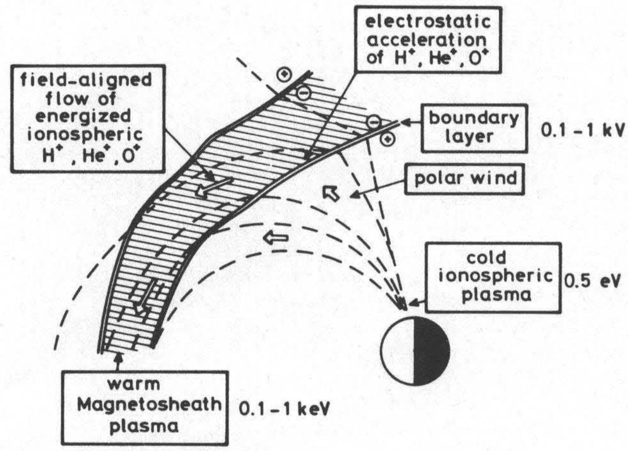

Figure 7. Schematic representation of a solar wind plasma element engulfed in the magnetosphere. The leading surface of the density irregularity is an (oblique) electrostatic shock separating the warm magnetosheath-like plasma from the magnetospheric and ionospheric plasma. Polar wind ions can be accelerated upwardly by the potential difference across the thin surface layer and form field aligned ion beams in the Plasma Boundary Layer of the magnetosphere. The plasma filament expands and spreads along the geomagnetic field lines interconnected with magnetic field lines inside the intruding volume element.

The Plasma Boundary Layer extending sometimes one Earth radius earthward from the magnetopause layer can be viewed as the stopper region where all plasma irregularities with any excess of momentum are eventually slowed down (Ref. 19). The thickness of this PBL should therefore depends on the degree of irregularity of the impinging solar wind momentum density, but it should also be a function of the integrated conductivity along the polar cusps field lines. A nearly uniform and steady solar wind would give a very thin PBL. For a very inhomogeneous solar wind flow the penetration distance of the plasma irregularities increases and the thickness of the PBL must be larger. Furthermore, since the ionospheric conductivity is modulated by seasonal variations one could expect annual variation in the average PBL thickness as well.

The presence of a well developed PBL should also depend on the orientation of the Interplanetary Magnetic Field direction. Indeed impulsive penetration across different parts of the magnetopause is favored when the IMF assumes certain orientations (Ref. 9). The correlation between the thickness of the Plasma Mantle and the southward component of the IMF shown in Refs. 32 and 33 supports this conclusion.

The impulsive penetration model can also account for Carlson and Torbert's observations better than any steady state model of the interaction between the solar wind and the magnetosphere. Indeed during two rocket flights in the dayside cusps Carlson and Torbert (Ref. 34) observed magnetosheath-like ions and electrons injected impulsively into the magnetosphere and precipitating into the cleft ionosphere. The dynamical ion spectra shown in Fig. 6 have been interpreted as a series of solar wind plasma irregularities injected along dayside cusps geomagnetic field lines at a distance corresponding to the magnetopause (9 - 19 R_E). Extrapolation of the dispersion lines in the high energy limit determines the instants of the successive injection events. The observations of impulsive injections of magnetosheath-like particles down to rocket altitudes are direct evidences that solar wind plasma irregularities are thrown into the magnetosphere impulsively as suggested in Ref. 8.

Fig. 7 illustrates a detached magnetosheath-like plasma intrusion engulfed into the magnetosphere. The presence of a current carrying plasma modifies locally the magnetic field distribution. The geomagnetic field is in general interconnected with the magnetic field inside the plasma element. Magnetic field lines traverse the thin current sheet separating the solar wind plasma element from the magnetospheric plasma. Charge separation electric fields normal to the plasma surface maintain local quasi-neutrality. In practice extremely small excesses of protons or electrons densities are sufficient to satisfy Poisson's equation. Lemaire and Scherer (Ref. 35) have calculated an electric potential distribution along a magnetic field extending from the dayside ionosphere up into a magnetosheath-like plasma element (see Fig. 8). The sharp potential drop of 25 Volts at 10.000 km altitude separates the warm magnetosheath plasma ($T_{e,w} = 10^6$K, $T_{p,w} = 7 \times 10^6$ K, $n_w = 10\,cm^{-3}$) from the cold ionospheric polar wind plasma ($T_{e,c}$ = 3,500 K;

$T_{O^+} = 1500$ K; $T_{H^+} = 3{,}000$ K; $T_{He^+} = 3{,}000$ K ; $n_{e.c} = 27{,}000$ cm^{-3}, see Ref. 35. The electrostatic shock transition accelerates cold ionospheric ions upwards and imparts them a certain amount of parallel energy. Narrow helicoïdal beams of H^+, He^+ and O^+ ions result from the electrostatic acceleration. The presence of accelerated ionospheric ions in the Plasma Boundary Layer and in detached plasma intrusions is therefore to be expected. The kinetic solution shown in Fig. 8 is not unique, however. In general the electrostatic shock front is propagating downwards and the electric potential is not necessarily a monotonic decreasing function of the altitude as in the case shown in Fig. 8. The charge separation electric field distribution across the plasma boundary can for instance reverse direction.

The electrostatic field distribution within an electrostatic shock does not prevent the whole structure to propagate downwards along the magnetic field lines. An excess of total pressure in the plasma irregularity will drive its edge toward lower altitude. This increases the volume of the element and reduces the excess of density and pressure inside the engulfed filament. A steady state solution like that illustrated in fig. 8 can eventually be reached when the sum of kinetic and magnetic pressures balance each other on both sides of the collisionless shock transition. Time dependent models of propagating electrostatic shocks driven by the field aligned the expansion of engulfed magnetosheath-like elements seem to be necessary to interpret quantitatively the precipitation events observed by Carlson and Torbert (Ref. 34).

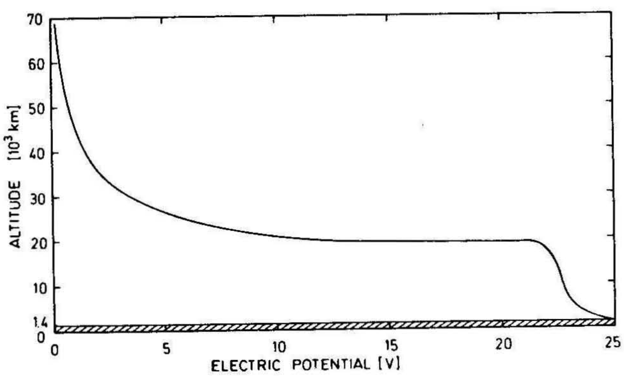

Figure 8. Electrostatic potential distribution along a polar cusps field line. The potential difference between the ionosphere and the high altitude magnetosheath-like plasma element was arbitrarily taken equal to 25 Volt. The distribution of the electric potential obtained by an iterative method satisfies the quasi-neutrality condition of any point along the magnetic field line. The sharp potential drop near 20,000 km altitude separates the predominantly warm magnetosheath plasma from the cold ionospheric plasma (from Ref. 35).

4. REFERENCES

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