MAGNETOSPHERIC PROCESSES POSSIBLY RELATED TO THE ORIGIN OF COSMIC RAYS

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ABSTRACT

Two processes are discussed which violate the frozen-in condition in a highly conducting plasma, reconnection and the auroral acceleration process. The first applies to situations in which $\beta = \frac{8\pi p}{B^2} \approx 1$. It plays an important role in the interaction of the solar wind with the Earth's magnetic field and controls energy input into as well as energetic particle release from the magnetosphere. Detailed in situ studies of the process on the dayside magnetopause reveal its transient and small-scale nature. The auroral acceleration process occurs in the low magnetosphere ($\beta << 1$) and accompanies sudden releases of magnetic shear stresses which exist in large-scale magnetospheric-ionospheric current circuits. The process is interpreted as a kind of breaking. The movements of the magnetospheric plasma which lead to a relief of the magnetic tensions occur in thin sheets and are decoupled along the magnetic field lines by parallel electric potential drops. It is this voltage that accelerates the primary auroral particles. The visible arcs are then traces of the magnetic breaking process at several 1000 km altitude.

1. INTRODUCTION

There are three ways in which a cosmical plasma can interact with a self-gravitating system. They depend on the existence of an extended atmosphere and/or an appreciable intrinsic magnetic moment. If the system is lacking both of these qualities completely, the plasma will impinge directly on it, as, for instance, the solar wind does on the moon. In case of a zero or weak magnetic moment, but with the existence of an extended atmosphere, the plasma will interact with the latter via its ionized component. In the solar system, examples of this class are the comets and the planet Venus.

The existence of a strong magnetic field shifts the location of interaction outside the atmosphere. It is typically collision-free in

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nature, although the magnetic field can transport the forces towards the central body where collisions are important. A *magnetosphere* is being created. It is the region in which the magnetic field linked to the self-gravitating system dominates the forces acting on the plasma component. Examples in the solar system are provided by the Earth, Mercury, perhaps Mars, Jupiter, Saturn, possibly Neptune and Uranus.

What is the possible relevance of the study of planetary magnetospheres to the origin of cosmic rays? It can be threefold. (1) Planetary magnetospheres are emitters of energetic particles and thus contribute - although on a modest scale - to the low energy end of the cosmic ray spectrum. (2) Since we have direct access to the regions where the particles are accelerated, we can probe into the processes and the detailed plasma and field configurations in which they operate. (3) We can study the electromagnetic radiation emitted from acceleration regions and thus try to calibrate the emissions with respect to the properties of the exciting particle beams, with the aim to apply this knowledge to cosmical sources.

In this contribution, I want to deal with the second aspect, and among all possible acceleration processes only with two of them, reconnection and the auroral acceleration process. Both are of universal importance. Although the first one has been known conceptually since more than twenty years and has been studied extensively, we are only now beginning to collect conclusive direct observations of this process in the magnetosphere. There are several unexpected features emerging that should be taken into consideration when studying other reconnection situations.

The second process is much less known. It does not even have a name apart from its auroral context. But there are good reasons to believe that it is rather universal. In purely physical terms, it could be briefly described as the set-up of large voltages parallel to the magnetic field direction in the presence of strong field-aligned currents and as a consequence of current-driven instabilities. The parallel voltage is, however, only one aspect of the process. Large transverse interchange motions are accompanying it. Disruptions as known to occur in Tokomaks may be of similar nature. For the time being, we may just call it "the auroral acceleration process" keeping in mind that it does not underlie all kinds of aurora, but rather the structured arcs. In the light of a new theory which I will characterize later we will find another, more descriptive name for this process.

2. RECONNECTION

Reconnection or merging of two oppositely directed magnetic fields in a highly conducting fluid has been first studied in the astrophysical context by Sweet (1958) and Parker (1957). Dungey (1961) applied it to the magnetosphere and proposed the general scheme of magnetic flux transport between the dayside and nightside magnetosphere. Although it has undergone substantial modifications, this scheme is still believed to be valid. Depending on their orientation, interplanetary magnetic field lines carried past the magnetopause by the solar wind can connect temporarily with the Earth's field. Such field lines are then called "open". They give the solar wind an easy means to transfer flow momentum to the magnetospheric plasma via magnetic shear stresses and drag it into the antisolar direction. Thereby, the field is being stretched and a magnetic tail is formed. The central region of the tail which contains a layer of hot plasma, the so-called plasma-sheet, separates stretched fields of anti-parallel direction. They are subject to the merging or reconnection process under circumstances which are not yet fully understood. This occurs in events of typically 1 hour duration which are called "substorms". As a result, open field lines are transformed into closed ones (i.e. dipole-like field lines) plus field lines that are completely disconnected from the Earth and are carried away by the solar wind flow. Internal convection motions carry the closed magnetic flux-tubes back towards the dayside where the process can eventually start again.

The physics of reconnection events in the tail, the substorms, is subject to intense study by magnetospheric physicists and much could be said about it that might have a bearing on the origin of cosmic rays. A good overview of substorms is contained in a recent text-book by Akasofu (1977). However, we are still lacking fully convincing data sets on the very process, much of the inferences are indirect.

On the front-side of the magnetopause, we are on somewhat safer grounds. Data have become available which allow quantitative checks of the predictions of the macroscopic theory of reconnection. Temporal and spatial scales of the process can as well be inferred. Therefore, and because our laboratory has been strongly involved in this area of research, I will deal in detail with the reconnection at the front-side of the Earth's magnetopause.

Before we enter this discussion, we may pause for a moment and ask ourselves what role reconnection could play in the production of cosmic rays. It can contribute to it in three ways. (1) Some of the magnetic energy released in the merging process is being transferred directly to suprathermal particles which appear at the lower end of the energy spectrum of cosmic rays. (2) Reconnection can modulate the energy input into a magnetic configuration where part of it is stored as magnetic energy. This can be used to some extent for the production of high-energy particles by unspecified internal processes. (3) Reconnection may then lead to a modulation of the storage of such high-energy particles, i.e. it may control their eventual leakage from the "accelerator" into interstellar space. At the present state of knowledge we cannot say even for the Earth's magnetosphere what dominates, the direct production of low energy cosmic rays during the reconnection process or the acceleration in the strong field of closed configurations and subsequent release from them. But there is no doubt that reconnection is an important contributor to the origin of cosmic rays.

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In view of the great interest in that process and of the many satellites launched with the aim of investigating the magnetosphere, it is rather surprising that it took so long to identify it unambiguously by in situ measurements. All what is needed is the combination of a magnetometer and a plasma detector capable to establish the flow of the dominant plasma component in three dimensions. As it turns out that the process is rather short-lived, both measurements must be made sufficiently fast and afford a high telemetry rate. The International Sun-Earth Explorers, ISEE 1 and 2, were the first satellites with the right orbits and instruments to meet these conditions. Paschmann *et al.* (1979) report an event of a few minutes duration at the dayside magnetopause near noon in which the observed changes of flow momentum at the magnetopause are consistent with the magnetic stresses that would exist if the internal and external fields were connected through a rotational discontinuity.

Whatever the detailed structure of a reconnection region may be (Petschek, 1964; Vasyliunas, 1975), it should contain a rotational discontinuity in which the magnetic field changes direction by a large angle and has a finite component normal to the plane of the discontinuity. This is sketched in Figure 1 for the simple case of almost anti-parallel fields. The plasma that transits through the discontinuity should undergo little change of its thermodynamic properties, but be accelerated by an amount that is related to the balance of magnetic and mechanical stresses which (in an isotropic plasma) reads:

$$[\rho \underline{v}_t v_n] = [\frac{\underline{B}_t B_n}{4\pi}] \quad . \tag{1}$$

Index "n" and "t" refer to the normal and tangential components, respectively. Square brackets indicate the jump across the discontinuity. Since B_n = const. and $\rho \cong$ const., we have the simple relations:

$$[\underline{v}_t] = \frac{[\underline{B}_t]}{\sqrt{4\pi\rho}} \tag{2}$$

and

$$v_n = \frac{B_n}{\sqrt{4\pi\rho}} \quad , \tag{3}$$

which the plasma should obey. The jump in tangential flow velocity (Equation 2) is easily observable, in contrast to the quantities of Equation 3. The reason is that on the one hand most theories predict small normal components, and on the other hand one or even two satellites are not sufficient to establish with sufficient confidence the normal vector of an observed discontinuity.

In earlier studies of the plasma flow at the magnetopause (Heikkila, 1975; Paschmann *et al.*, 1976; Haerendel *et al.*, 1978), it was quite

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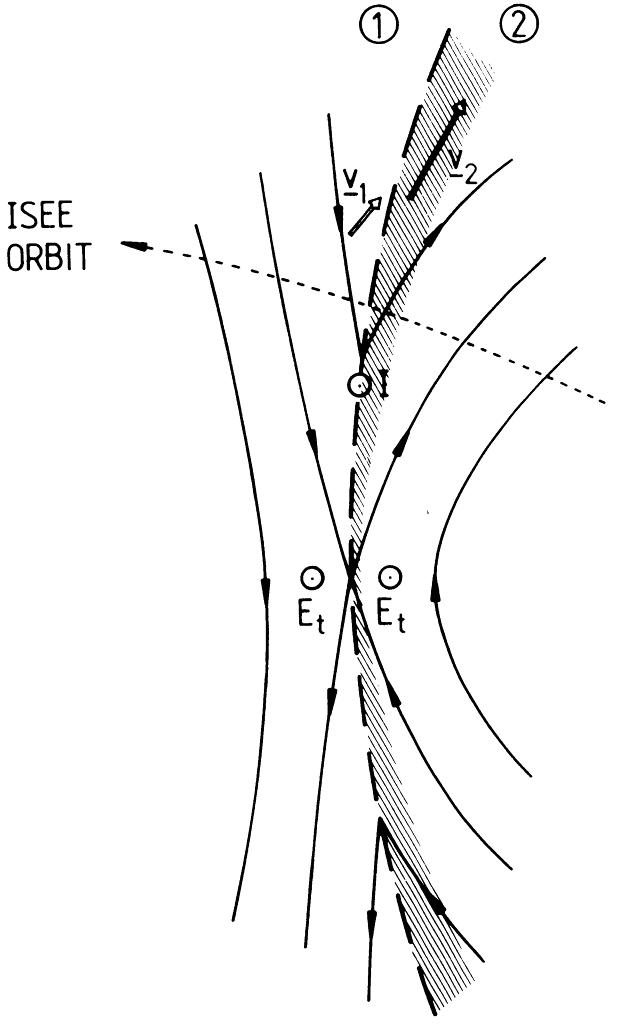

Figure 1. Reconnection situation at the dayside magnetopause with southward pointing interplanetary field. The shaded area shows a layer of accelerated plasma flow after transition of the solar wind through the rotational discontinuity (Paschmann *et al.*, 1979).

disturbing that the predictions of Equation 2 were not encountered even when the magnetic fields inside and outside the magnetopause were almost oppositely directed. It became evident that if reconnection occurred at all in the explored regions it should be transient and small-scale in nature and thus escape detection. The recent measurements of Paschmann *et al.* (1979) were, however, sufficiently fast to cope with this difficulty. Figure 2 shows a set of data on three subsequent transitions through the magnetopause along a pass as sketched by the dashed line in Figure 1. The displayed data are total plasma density, N_p, magnitude of the flow velocity, v_p, the component of $\underline{B}$ perpendicular to the ecliptic, B_z, the plasma pressure P and magnetic pressure, B, and finally, the sum of gas and magnetic pressures, P_T. The units are, respectively: cm^{-3}, km/sec, nT, and 10^{-7} N m^{-2}. The magnetopause (MP) undergoes usually radial oscillations; hence there are three transitions as revealed most clearly by the jumps of B_z from positive to negative values. The most important feature is the large increase of plasma flow velocity by several 100 km/sec just inside the magnetopause. Via the total density measurements which the same instru-

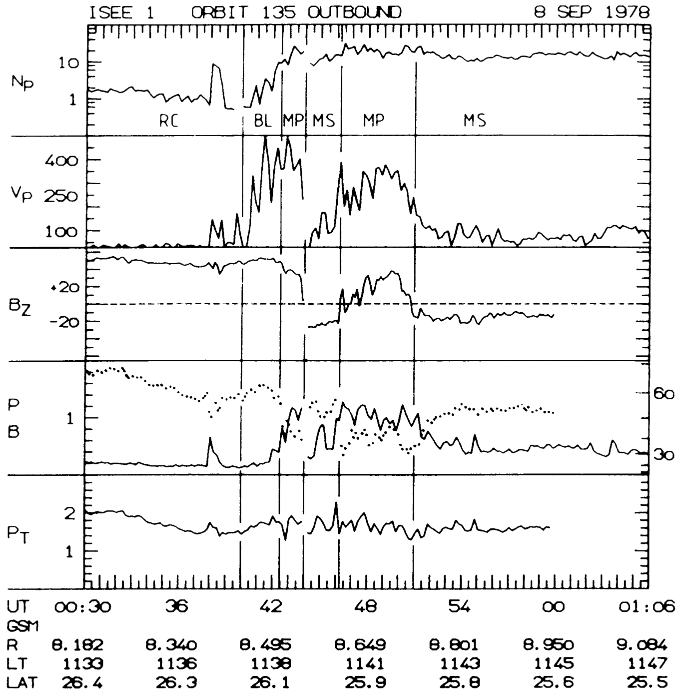

Figure 2. Plasma and magnetic field data from a transition of ISEE 1 through the magnetopause near local noon. N_p, V_p, B_z, P, B, and P_T are plasma density, flow speed, component of $\underline{B}$ normal to the ecliptic, gas and magnetic pressures and the total pressure, respectively. The units are cm^{-3}, km/sec, nT, and 10^{-7} N m^{-2}. The symbols RC, BL, MP, MS designate the different plasma regimes encountered, namely ring current, boundary layer, magnetopause layer, magnetosheath (i.e. shocked solar wind) (Paschmann *et al.*, 1979).

ment yields and the magnetometer data, Equation 2 can be checked. Agreement is found within 10%. This must be considered as rather good in view of several sources of experimental error.

A special technique developed by Sonnerup (1971) and co-workers, which is called "minimum variance technique", allows the derivation of B_n if the orientation of the discontinuity is sufficiently stable during the transit time of the satellite. For the event contained in Figure 2 an inward pointing normal component of 5.4 nT was found. An inward flow component of 28 km/sec would go along with this value (Equation 3). The existence of two closely spaced spacecraft (ISEE 1 and 2) allows the determination of the speed of normal motion of the magnetopause. This is needed to correct the value found for v_n by a similar minimum variance technique. Though affected by large error bars both values are in good agreement.

I have chosen to discuss this particular measurement in detail in order to give the reader some feeling for the difficulties involved in establishing with great confidence the existence of a fundamental plasma process in space, even under rather favorable circumstances. Meanwhile about 10 events of this kind have been identified, approximately 30% of the total number of cases in which the orientation of the interplanetary field was favorable for reconnection. Strong anti-parallel field components are apparently not sufficient for the process to occur. What a sufficient condition could be, is not known at this moment.

Earlier studies of the plasma near the magnetopause (Hones *et al.*, 1972; Akasofu *et al.*, 1973; Rosenbauer *et al.*, 1975; Paschmann *et al.*, 1976; Haerendel *et al.*, 1978) had revealed an important feature of the magnetopause. It is covered on its inside by a boundary layer which covers it down to the distant tail. It is particularly thick and dense in the region of the polar cusps, which is shown in Figure 3. Here it

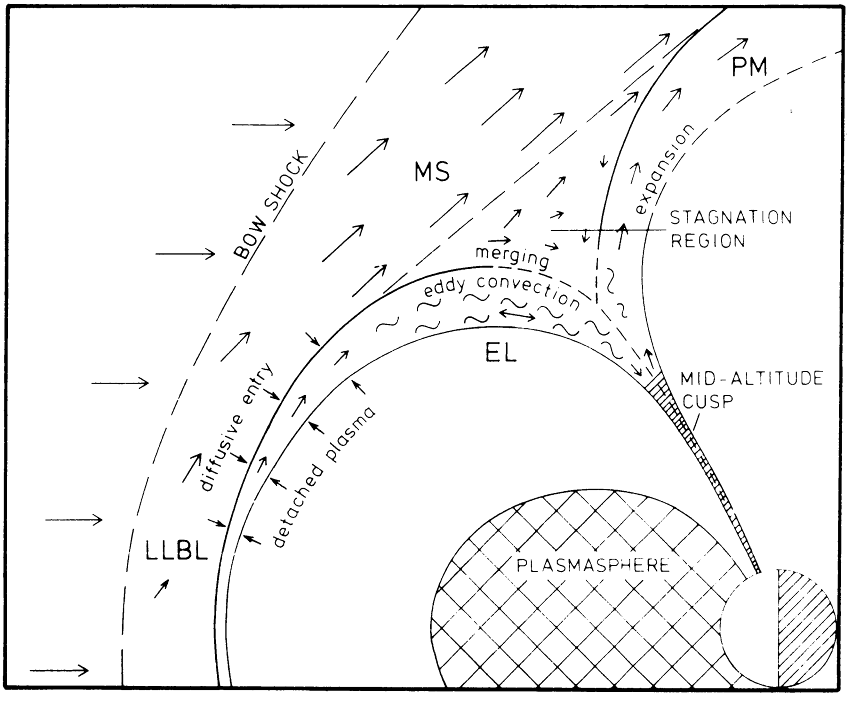

Figure 3. Meridian cut through the frontside boundary layers with indication of the dominant processes (MS = magnetosheath, LLBL = low latitude boundary layer, EL = entry layer, PM = plasma mantle) (Haerendel *et al.*, 1978).

has been given the name "entry layer" (EL), since it is believed that this is the region of dominant plasma entry into the magnetosphere. Only a small fraction of the plasma in this part of the boundary layer penetrates along the field lines into the polar region. Most of it flows along the tail boundary layer into the distant tail. This part has been called "plasma mantle" (PM). The boundary layer on the low-latitude dayside (LLBL) is rather thin, of lower density then in the adjacent solar wind (magnetosheath (MS)) and exhibits strong temporal modulations.

If the cusp regions play a dominant role in plasma entry, they should also be the location of frequent reconnection events (Haerendel, 1978). From the observation of very irregular flows in the entry layer it was concluded that these events should be transient and small-scale in nature. Scales of only 1000 km and 20 sec have been deduced from measurements with insufficient temporal resolution on the ESA satellite HEOS 2. This feature was probably also responsible for our inability to identify, in the same manner as discussed before, the signature of reconnection. However, the irregularity of the flow gives ground to the hypothesis that the mass transport inside the boundary layer is a kind of eddy convection process. An order of magnitude estimate of its efficiency is consistent with the implications of the drainage of this region by the mantle flow (Haerendel, 1978).

A more recent study of the low latitude part of the dayside boundary layer by Sckopke *et al.* (1980) has revealed its transient nature rather clearly. Here the time-scales are, however, much longer. They are of the order of a few minutes and the spatial scales of several Earth's radii. Of the three possible interpretations of the observations which are shown in Figure 4, case (c) appears as the most likely. This means

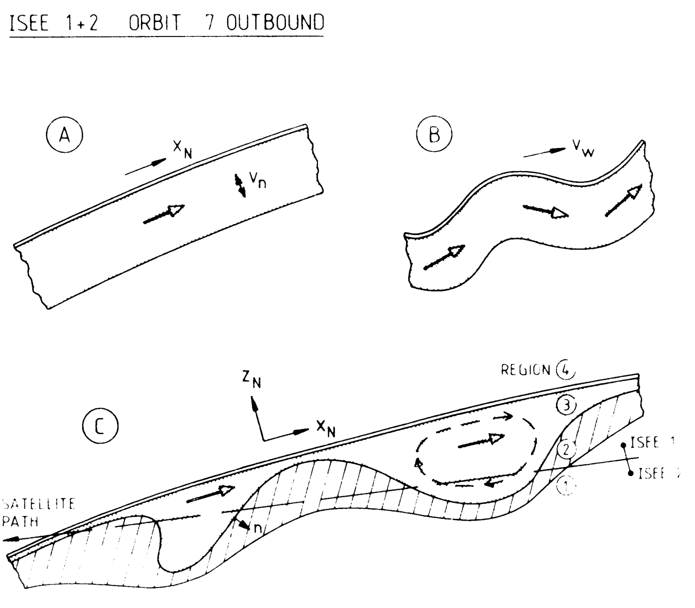

Figure 4. Possible interpretations of transient encounters of the low latitude boundary layer with ISEE 1 and 2. The circulation indicated in (c) is to be seen in a frame moving with the overall structure (Sckopke *et al.*, 1980).

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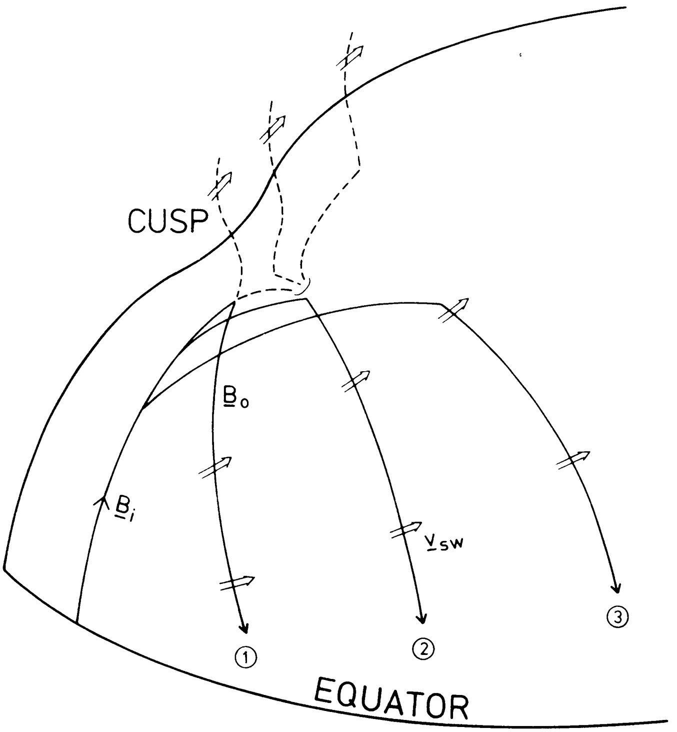
that plasma is carried in form of separate "blobs" along the inside of the magnetopause in the downstream direction. The expected rotational motion of the plasma inside and outside the boundary layer has been confirmed observationally. In the event that has been extensively studied by Sckopke *et al.* (1980), the bending of the magnetic field inside the boundary layer is in a sense as if the plasma were pulled from above, i.e. the cusp region. This is again consistent with dominant reconnection in the cusps. The periodicity of the events on the low latitude side may be related to the separation of "vortices" from the stagnation region (shown in Figure 3) outside the cusp magnetosphere, as it would happen in an ordinary fluid streaming around a corner (Haerendel, 1978). It could also be the consequence of a Kelvin-Helmholtz instability of the boundary layer flow (Sckopke *et al.*, 1980).

The consequences of reconnection in the cusps on the gross topology of the field is shown in Figure 5 taken from Haerendel *et al.* (1978).

Figure 5. Sketch of the erosion of magnetic flux from the front-side of the magnetosphere initiated by reconnection in the cusp regions (Haerendel *et al.*, 1978).



Magnetic flux is being eroded from the front-side of the magneto-sphere. On the low latitude side, the magnetic field becomes stretched, i.e. its magnitude increases, as it is often observed. This means that reconnection does not necessarily imply a release of magnetic energy everywhere. Part of the space involved may experience a growth of magnetic energy at the expense of kinetic energy of flow. The erosion of magnetic flux occurs in short-lived events of tens of seconds to a few minutes. Sometimes such flux-tubes can be identified outside the magnetopause in the solar wind plasma (Russell and Elphic, 1979). In addition to the magnetic signature (increase of $|\underline{B}|$) one finds also hot electrons streaming away from the magnetopause. They may have been accelerated at the magnetopause or released from the interior. Whatever the origin of these energetic electrons is, we seem to observe an important step in the production of energetic particles by a magnetosphere.

A more important source of energetic particles is actually the geomagnetic tail (Anderson, 1965; Baker and Stone, 1976; Hones *et al.*, 1976; Sarris *et al.*, 1976). Again it seems that part of the energization is due directly to the tail reconnection process and part to a leakage of the energetic trapped particles from the outer radiation belt when the tail recovers after a reconnection event ("recovery phase" of a substorm) (Belian *et al.*, 1980).

In summary, we find the following properties of the reconnection process in the Earth's magnetosphere. It is transient and small-scale, i.e. the spatial scale is much smaller than the size of the overall magnetic configuration. These scales may be connected to the hydrodynamic properties of the plasma flow around the object (turbulence). The cusp regions seem to be the primary site of the reconnection process. Boundary layers inside the magnetopause are set up as a consequence. The short duration of the reconnection events leads to the erosion of magnetic flux in form of rather discrete flux-tubes, which provide paths for the escape of energetic particles from the interior. At the same time, direct acceleration of energetic particles is observed.

When applying theoretical models of reconnection to an astrophysical system, we should be warned that it may be dangerous to use a stationary picture and scales of the size of the overall system as suggested by the well-known model of Petschek (1964) and its successors. As observable in so many phenomena, the plasma seems to "like" the formation of small-scale structure, filaments. We must learn to understand the causes of this behavior in order to be able to make predictions for other situations. It is quite clear that the efficiency of a process is quite different when it is small scale and transient from what it would be when it is large scale and stationary.

3. AURORAL ACCELERATION PROCESS

There is an intimate relation between reconnection and the auroral acceleration process. Both processes violate the frozen-in condition of the magnetic field in a highly conducting plasma. We are used to call it reconnection or merging when it happens in a plasma with $\beta = \frac{8\pi p}{B^2} \approx 1$. But magnetic lines of force can as well become reconnected when $\beta \ll 1$. It means that there is a shear of the transverse convection. Plasma that was distributed along a certain flux-tube at a certain time will be found on separate flux-tubes a moment later. The most striking visible expression of such an event was provided once by a barium ion jet experiment in the auroral magnetosphere (Wescott *et al.*, 1976). The upper part of a narrow barium ion streak which extended over a height range of many 1000 km broke suddenly into a sheet of parallel streaks which kept growing and dispersing, while the lower end ($\lesssim$ 5500 km) remained in its initial form. All this started when the flux-tube loaded with barium plasma came into contact with an auroral arc.

A quasi-stationary field-aligned shear of the transverse plasma motion, i.e. of the transverse electric field, can only exist in the presence of a parallel electric field. The occurrence of such fields with magnitudes much higher than what was to be expected on the grounds of the electrical conductivity was suspected long before the first direct measurements. The evidence came mainly from observations of the velocity distribution of primary auroral particles and anti-correlations of electrons and positive ions (protons) (e.g. Evans, 1975). Pronounced peaks in the energy spectrum at a few keV and field-aligned velocity distributions are typical for the electrons which generate structured auroral arcs. From their velocity dispersion one could also deduce that the electrostatic acceleration regions must be located at typically 1 R_E altitude, not in the distant magnetosphere. First direct experimental proof was provided by another barium ion jet experiment which showed clearly the upward field-aligned acceleration of barium ions by 5 keV at an altitude of 7500 km at the moment when a bright auroral arc developed at the projection points to the 100 km level (Haerendel *et al.*, 1976).

It was only recently that extensive direct measurements inside the acceleration regions became available (Shelley *et al.*, 1976; Mozer *et al.*, 1977; Mizera and Fennell, 1977). They were obtained with the US Air Force satellite S3-3 on an elliptical polar orbit with 8000 km apogee. From all these measurements a heuristic model of the acceleration region was developed which is sketched in Figure 6. Strong transverse electric fields exist in thin sheets extending in E - W direction. The equipotential contours do not extend all the way to the ionosphere, but close at heights of several 1000 km. These regions are imbedded in sheets of intense field-aligned electric current emerging from the ionosphere. The current when directed upward is essentially carried by the energetic (few keV) primary auroral electrons which have undergone a linear acceleration in the region of $E_{\parallel} \neq 0$. Streams of keV protons, helium and oxygen ions are as well observed to emerge from these regions in the upward direction. Some have field-aligned distributions (protons), others (dominantly oxygen) have so-called conical distributions indicating the presence of additional strong transverse heating in the acceleration regions (Sharp *et al.*, 1977). In addition, high amplitude plasma waves are present which have been identified as ion-cyclotron and lower hybrid waves and low frequency turbulence (Mozer *et al.*, 1977; Kintner *et al.*, 1978; Temerin, 1978). A coherent review of the observational facts and their physical interpretation has been given by Mozer *et al.* (1980).

The acceleration regions have been interpreted in terms of electro-

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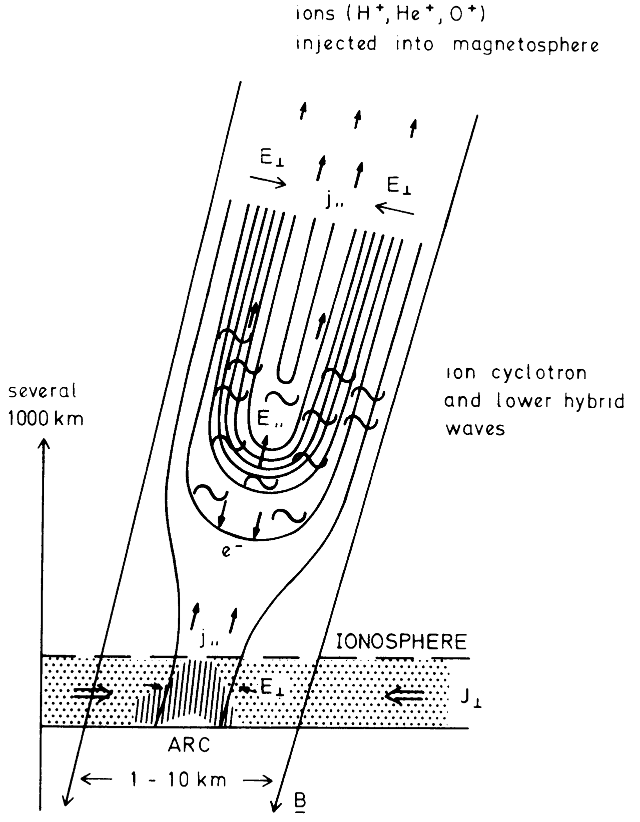
Figure 6. Phenomenological model of the auroral acceleration region above structured arcs at heights of several 1000 km. Strong transverse electric fields, $E_\perp$, are decoupled from the ionosphere by a region of $E_\parallel \neq 0$. The accompanying field-aligned current, $j_\parallel$, is carried mainly by accelerated electrons. Ions are injected upward and different plasma waves are excited.



static shocks (Swift, 1975; 1976), double layers (Shawhan *et al.*, 1978) and regions of high anomalous resistivity (Hudson *et al.*, 1978). It is fair to say that at this moment agreement on the basic physical process does not exist. Even the ultimate energy source feeding the acceleration region is a matter of debate. A convincing theory should provide answers to three basic questions:

(1) Why are the acceleration regions so narrow (as evidenced by the thinness of auroral arcs, typically 1 km)?

(2) What determines the strength of the electric current connected with the appearance of arcs?

(3) Why is the process located at several 1000 km altitude?

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Already in 1971 Kindel and Kennel have shown that a constant field-aligned current meets the condition for two-stream ion-cycotron and ion-acoustic instabilities in the low density plasma above ≈ 1000 km. This argument taken from linear instability theory may provide the basic answer to question (3). However, an argument involving the state of fully developed plasma turbulence (consistent with the observed wave-fields) would appear to be more satisfying. The exploration of various theoretical approaches to the understanding of the auroral acceleration process is at present in the center of magnetospheric research and presents one of the greatest challenges to the space plasma physicists.

I want to end this discussion with a brief outline of my own interpretation of the primary auroral process (Haerendel, 1980). The reader should be warned that a critical discussion of these ideas in the scientific community is just starting and that the elaboration of even the basic features of the model is still incomplete. The foundation of this theory is my conviction that the process is nothing else than another way of releasing magnetic energy stored in a magnetospheric-ionospheric current circuit. Under undisturbed conditions the energy is mostly dissipated by Ohmic losses in the ionosphere. Auroral arcs appear when at intermediate altitudes an effective resistance is building up which allows field-aligned potential drops, i.e. slippage of the magnetospheric plasma below and above the $E_{\parallel} \neq 0$ region with respect to each other. What is the nature of this slippage? It can only be in a sense as to carry the plasma and field configuration into a state of lower energy.

A simplified picture of the process is contained in Figure 7. The zero order magnetic field is taken as homogeneous. On either end of the system there are collision dominated regions representing the northern and southern ionospheres. In the center is a generator region representing the plasma sheet in the tail. Since the plasma is insulated from the central body by a non-conducting atmosphere it is usually in a state of slow convection ($\underline{v}_S$), which is determined by the strength of the generated current and the Ohmic resistance of the ionospheres. The mechanical forces driving the generator are balanced by the viscous forces acting in the ionospheres.

This situation can suddenly be disturbed at intermediate altitudes when the acceleration region develops with a resistance that exceeds that of the ionosphere. This means the plasma is free to move in a sense as to relieve quickly the magnetic tension with velocities v_f exceeding by far the undisturbed convection velocity v_S . The knowledge of this event is propagated by elastic shear waves along $\underline{B}$. Within a short time, τ , the whole field line participates in the relief motion, and the magnetic energy reservoir becomes exhausted. However, all this happens only in thin sheets so that there is plenty of free energy left in the transverse dimension inside the gross current circuit. The process is rather similar to the breaking or tearing of an elastic medium. Once a crack has been formed it will propagate into the stressed medium.

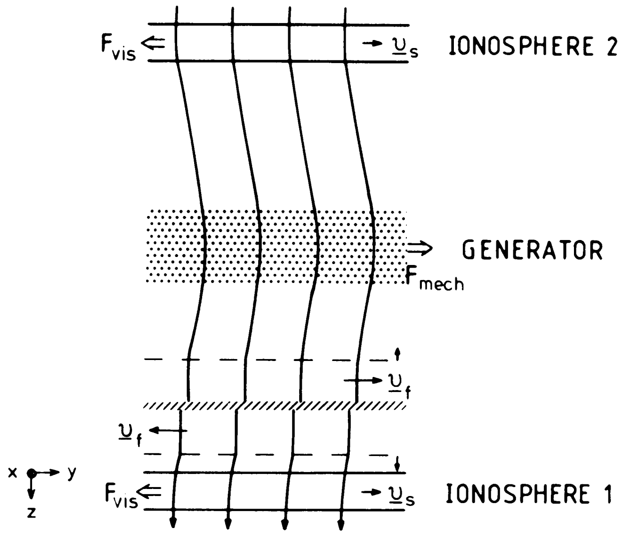

Figure 7. Simplified situation representing the dragging of field lines by the mechanical forces in the generator region (plasma sheet) and opposed by the viscous forces provided by the ionosphere. The resulting slow convection (v_s) can become disturbed by sudden stress releases (velocity v_f) at intermediate altitude, the knowledge of which spreads along $\underline{B}$ by means of shear Alfvén-waves (Haerendel, 1980).

In Figure 8 we are looking sideways into the magnetospheric-ionospheric current loop. The "fracture zone" is enlarged. It is shown to propagate slowly transverse to $\underline{B}$ with velocity u_F into the reservoir of magnetic energy while the information about the breaking, i.e. the set up of anti-parallel convective motions $\underline{v}_\perp$, is propagating behind two wave fronts along the lines of force with a speed of the order of the Alfvén-velocity (v_A). These fronts form a pair of nearly transverse, slightly oblique waves ($u_F << v_A$) attached to the nose of the "fracture zone" , the diffusion region. In a triangular region behind a second pair of somewhat slower standing waves, the opposing convective motions and their corresponding transverse electric fields are decoupled by an $E_\parallel \neq 0$.

For the quantitative analysis it is essential to determine the strength of the current, J_1, flowing inside the standing discontinuities and the propagation speed, u_F. For the first we take as a measure the field-aligned current density, $j_\parallel$, emerging from the ionosphere multiplied by the width, w , of the region. $w \hat{=} u_F \cdot \tau$, where τ is the travel time of an Alfvén-wave to the ionosphere and back. It is easy to see that the speed of convection switched on behind the first pair of

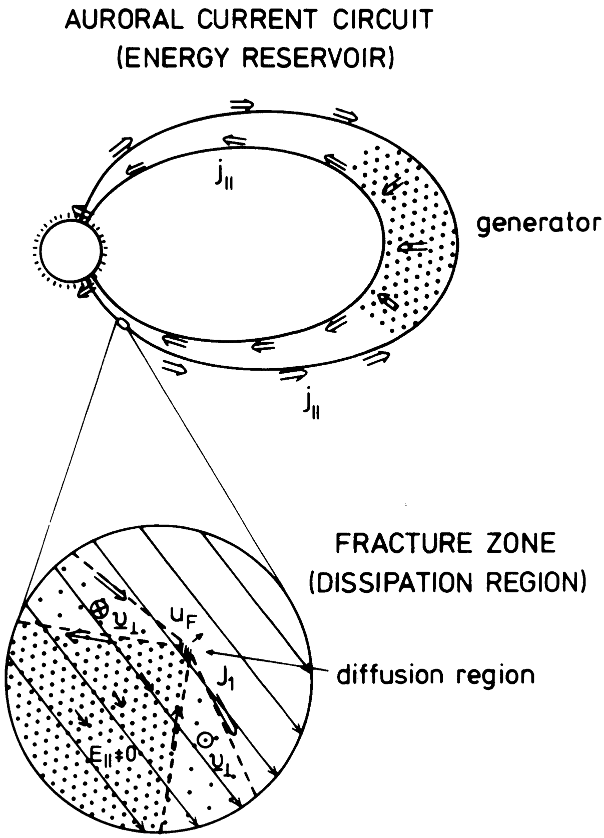

Figure 8. Meridian cut through the magnetospheric-ionospheric current circuit with an enlarged view of the "fracture zone" at low altitudes. This region is structured by discontinuities (dashed lines) which are super- and sub-Alfvénic shear waves. They switch on and off a high transverse convection, $v_\perp$, and $E_\parallel \neq 0$ (Haerendel, 1980).

standing waves is:

$$v_\perp = \frac{c}{B} \cdot M_{n1}^{-1} \cdot \frac{4\pi v_A}{c^2} \cdot J_1 \qquad (4)$$

with $J_1 = j_\parallel \cdot w$.

M_{n1} is the Alfvênic Mach-number of the first pair of waves. It has been shown by the author (Haerendel, 1979) that generalized Alfvén-waves exist which propagate with super- or sub-Alfvênic velocity if one allows for a jump of $E_\parallel$ across the discontinuity and conserves as usually mass, momentum, energy and magnetic flux. These waves are thought to structure the acceleration region in the manner sketched in Figure 8. In contrast to pure Alfvén discontinuities (intermediate waves) the thermodynamic properties of the plasma are strongly changing upon transition through the waves; the entropy increases.

The propagation of the "fracture zone" with speed u_F is regarded as a diffusion or rather heat conduction process caused by the pressure difference of the plasma in front of and behind the discontinuities. For this process, the transverse mobility is of great importance. It must be non-classical, i.e. of anomalous nature. We measure it by an effective transverse collision frequency, $\nu_\perp^*$, in units of the ion-cyclotron frequency, Ω_i:

$$\nu_\perp^* = \alpha_\perp \Omega_i \quad \cdot \quad (\alpha_\perp \approx 10^{-2}) \tag{5}$$

Taking all these elements together (Haerendel, 1980) one finds a characteristic current density, $j_\parallel$, for which the process can maintain itself:

$$j_c = M_{n1} M_{n2} \sqrt{\frac{e\ n\ c\ B}{2\ \pi\ \alpha\ \tau}} \quad , \tag{6}$$

where $M_{n1,2}$ are the respective Alfvênic Mach-numbers. This current density is not related to a linear instability analysis as carried out by Kindel and Kennel (1971), but represents a condition for the stationary release of magnetic shear stresses by the described non-linear process.

The other relevant quantities like width, voltage drop etc. can be deduced as well. This exceeds the scope of this paper. The width, w, is related to the ability of the medium to support a parallel field. When introducing an anomalous resistivity by means of an effective parallel collision frequency, $\nu_\parallel^*$, one finds:

$$w \approx \sqrt{\nu_\parallel^* \tau} \cdot \frac{c}{\omega_{pe}} \quad , \tag{7}$$

where ω_{pe} is the plasma frequency. Thus, the thinness of auroral arcs appears to be related to the electron inertial length, c/ω_{pe}, and the effective collision frequency.

It is also easy to see why this "breaking" of field lines should occur above the topside ionosphere. It is here that the critical current defined by Equation 6 and projected to the ionosphere assumes its lowest value, i.e.

$$\frac{n}{\tau B} = \min \quad . \tag{8}$$

The sketched theory provides answers to the above formulated questions (Haerendel, 1980). In addition, it allows quantitative estimates of $j_\parallel$, $v_\perp$, w, field-aligned voltage, energy flux, etc. which turn out to be quite consistent with the observations, if one makes a reasonable guess on the microscopic parameters $\alpha_{\perp}$ and $\nu_{\parallel}^{*}$. The Mach-numbers turn out as $M_{n1} \gtrsim 1$, $M_{n2} \approx 10^{-1}$.

The great general interest in the auroral acceleration process lies in the suspicion that it may be rather universal. Sheared magnetic fields occur in a wide variety of cosmical situations, e.g. planetary magnetic fields which are distorted by satellites (Io in the Jovian magnetosphere), twisted magnetic fields in the solar corona, magnetic fields pervading the accretion column of binary neutron stars which are subject to distortion by the Rayleigh-Taylor instability. It is tempting to apply Equations 6 and 7 to such situations. However, an appropriate discussion of the assumptions and involved parameters cannot be given here. One can easily see though that rather high energies may be attainable by this process in systems of much higher magnetic field. So, it may play a non-negligible role for the origin of cosmic rays.

4. FINAL REMARKS

It is difficult to do justice to two so important and little understood processes in a short paper of this kind. My main aim is to draw attention to recent progress in their exploration by in situ measurements and their interpretations. Once we have developed theories that allow to derive, from first principles, the key features observed, we may be in the position to apply this knowledge with some confidence to distant objects. This is the exemplary nature of magnetospheric research in the wider context of astrophysics.

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