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Global Problems in Magnetosphere Plasma Physics and Prospects for their Solution

J.G. ROEDERER

Geophysical Institute
University of Alaska
C.T. Elvey Building
903 Koyukuk Avenue North
Fairbanks, Alaska 99701
U.S.A.

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GLOBAL PROBLEMS IN MAGNETOSPHERIC PLASMA PHYSICS AND PROSPECTS FOR THEIR SOLUTION*

JUAN G. ROEDERER**

Dept. of Physics and Astronomy, University of Denver, Denver, Colo. 80208, U.S.A.

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Abstract. Selected problems of magnetospheric plasma physics are critically reviewed. The discussion is restricted to questions that are 'global' in nature, i.e., involve the magnetosphere as a whole, and that are beyond the stage of systematic survey or isolated study requirements. Only low-energy particle aspects are discussed. The article focuses on the following subjects: (i) Effect of the interplanetary magnetic field on topography, topology and stability of the magnetospheric boundary; (ii) Solar wind plasma entry into the magnetosphere; (iii) Plasma storage and release mechanisms in the magnetospheric tail; (iv) Magnetic-field-aligned currents and magnetosphere-ionosphere interactions. A brief discussion of the prospects for the solution of these problems during and after the International Magnetospheric Study is given.

1. Introduction

A magnetosphere arises from the interaction of a continuously streaming, hot, collisionless plasma with a magnetized body. In this interaction a cavity – the magnetosphere proper – is carved out in the flow by the magnetic field of the central body. This magnetic field also physically ties the points of the magnetosphere together, guiding charged particles, plasma waves and electric currents; trapping thermal plasma and energetic particles; and transmitting hydromagnetic stresses between the exterior flow and the resistive central body. Presently known magnetospheres scale from a few thousand kilometers in transverse dimension (Mercury) to over ten million light years (Radiogalaxy NGC 1265 – Figure 1). The principal energy source for magnetospheric processes may be the external plasma flow ('earth-like' magnetospheres) or the rotating magnetized body ('pulsar-like' magnetospheres). The plasma itself may come from the external flow (Mercury, Earth), from the central body (perhaps pulsars) or its ionosphere (Earth, Jupiter), or from satellites of the central body (Jupiter's satellite Io and Saturn's Titan), or all three. All known magnetospheres are highly time variable, exhibiting different variations upon a common theme: wherever nature creates a plasma system, she arranges for instabilities which cause magnetic energy stored in some region to be suddenly released, accelerating a small subset of charged particles to high energy.

Figure 2 (after Morfill and Quenby, 1971) qualitatively shows a possible steady-state magnetic field topology of a planetary magnetosphere, drawn in the plane defined by the magnetic axis of the planet and the bulk velocity vector of the solar

* Prepared for the Panel on Heliosphere Hydromagnetics of the National Academy of Sciences and for the Steering Committee of the International Magnetospheric Study.

** Present address: Geophysical Institute, University of Alaska, Fairbanks, Alaska 99701, U.S.A.

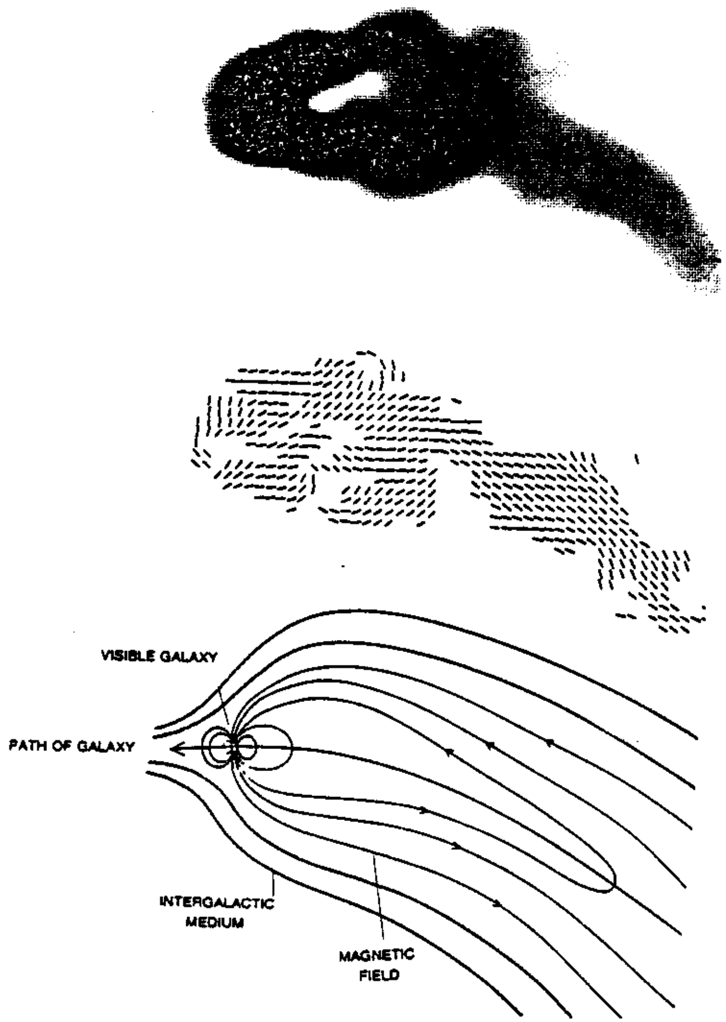

Fig. 1. *Top*: 21-cm-wavelength radio photograph of radiogalaxy NGC 1265 (Strom *et al.*, 1975). *Middle*: direction of the magnetic field in the gas. *Bottom*: magnetospheric model of the Galaxy.

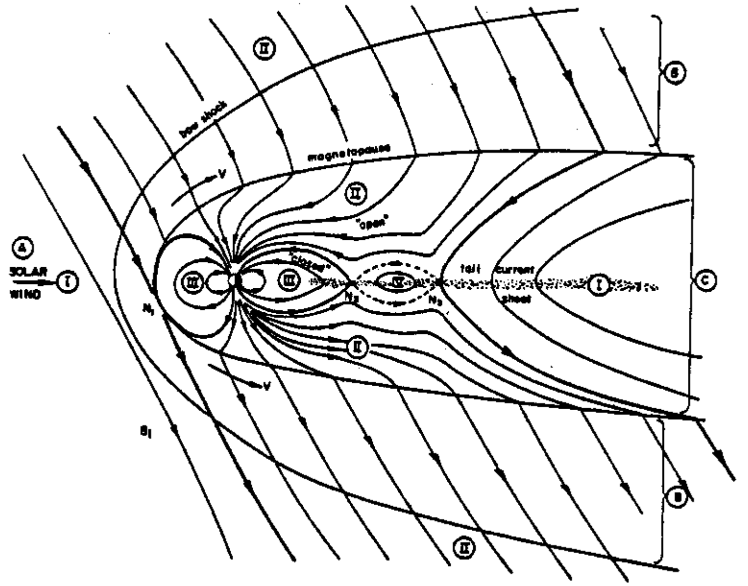

Fig. 2. Sketch of a possible steady-state magnetic field topology of a planetary magnetosphere, drawn in the plane defined by the magnetic axis of the planet and the bulk velocity vector of the solar wind. See text for an explanation of the regions marked.

wind. Four regions may arise, as defined by the topological features of their magnetic field lines. ***Region I*** comprises the family of field lines which emerge from the solar surface and return to it at another point.* They enclose source currents flowing in the interior of the Sun that are external to the plasma under consideration. ***Region II*** is defined by the field lines which link the Sun with the planetary body. ***Region III*** contains the field lines which intersect the planetary surface at two points; they encircle source currents flowing in the interior of the magnetized body which are independent of the plasma elsewhere. ***Region IV*** is one in which the field lines are totally embedded in plasma; they do not contact the Sun or the planetary body and only encircle external source currents. Under certain conditions region II could shrink to zero (the case of a 'closed' magnetosphere); region IV may exist only as a transient feature; it is conceivable that two or more such regions could exist simultaneously or that it could flatten to form an extended 'neutral sheet.'

These 'field-topological' regions are cut across by plasma boundaries that define distinct 'plasma-topological' regions (Figure 2). ***Region A*** represents the unperturbed supersonic solar wind plasma whose 'lower' boundary lies at the base of the

* Or eventually are connected to the interstellar medium.

(4)

corona. This lower boundary represents the acceleration region of the solar wind where the solar atmosphere is heated by local dissipation of hydromagnetic wave energy emitted from the photosphere. The local configuration of magnetic field and ambient gas determines the characteristics of the generated solar wind. For all practical purposes, the magnetic field and other plasma parameters of region A can be assumed to be uniform in the vicinity of the magnetosphere during steady-state conditions.* The standing bow shock represents the boundary with the magnetosheath, *region B*, containing initially compressed, subsonic and sometimes turbulent plasma that subsequently expands again to superalfvénic speed as it flows along the magnetospheric boundary. This boundary, the magnetopause, delimits the magnetospheric domain proper, *region C*. The bow shock and the magnetopause involve discontinuities of the magnetic field and of other plasma parameters. The lower ionosphere, or, in the case of planetary bodies devoid of an atmosphere, the planetary surface, represents the 'lower' boundary of region C.

The electric conductivity along magnetic field lines appears to be extremely high so that the MHD approximation (V: plasma bulk velocity)

$$\mathbf{E} + \mathbf{V} \times \mathbf{B} = 0 \tag{1}$$

is assumed to hold everywhere in the system of Figure 2, with the following exceptions: (i) near the solar surface, i.e., for all practical effects, at the base of the corona; (ii) near the magnetized body in the lower ionosphere or on the planetary surface; (iii) on and near the bow shock; (iv) on and near the magnetopause; (v) in the vicinity of those points where the magnetic field vanishes (N_1, N_2, N_3 in Figure 2). In addition to the above, there may be spatially and/or temporally limited regions (e.g., field lines which guide auroral particles) where an anomalous conductivity (turbulence along field lines) and/or parallel electric fields sustained by pitch angle anisotropies invalidate the MHD approximation.

Note again that region IV (Figure 2) would be the only one in which magnetic field lines are totally embedded in the plasma of the system; all other regions contain field lines along which plasma is allowed to spread 'freely' (without resistance) only within certain boundaries. Within such boundaries and wherever the MHD relation (1) holds, the magnetic field lines will be electric equipotentials in a steady-state configuration (one that changes on a time-scale long compared to the time it takes to short out any electric field component parallel to the magnetic field).

In this article we shall concentrate on region C (Figure 2) and its boundaries, i.e., the magnetosphere proper. On occasion, we shall have to deal with the characteristics of the magnetosheath, region B. The perhaps most fundamental problem of magnetospheric physics is to determine the field- and plasma-topological features of Figure 2 that are permanent characteristics of the interaction of a supersonic plasma flow against a magnetized, resistive central body, to identify all transient properties,

* This certainly does not apply to Jupiter's magnetosphere, whose impressive size (over 0.1 AU transverse dimension) compares with the scale-size of major solar wind inhomogeneities. See also remarks on p. 37.

and to establish a self-consistent, quantitative theoretical description of the cause-and-effect relationships between the intervening parameters. Unless otherwise stated, we shall refer to the terrestrial magnetosphere only and break up the abovementioned fundamental problem into several global 'subproblems,' each one focusing on certain chains of interaction mechanisms that involve the magnetosphere as a whole. In this discussion, the 'external' boundary conditions of relevance to the magnetosphere proper will be represented by the given values of magnetic field, bulk velocity, density and temperature of the solar wind immediately in front of the bow shock, and by the values of similar parameters plus the local resistivity in the ionosphere.

It must be emphasized that *we shall focus only on plasmaphysical problems that are of truly 'global' nature, i.e., involve the magnetosphere as a whole, and that are beyond the stage of systematic survey or isolated study requirements*. The picture presented and the research work quoted are far from complete; no original data will be shown. Because of the severe restriction in scope, there are four capital omissions, referring to fundamentally important problems of magnetospheric research. One omitted subject is energetic trapped particles, the ring current, and wave-particle interactions. Another is transient parallel electric fields and auroral particle acceleration; the third is the study of the composition of magnetospheric plasma; and the fourth, physics of the plasmasphere.

2. Problem No. 1: Effect of the Interplanetary Magnetic Field on Topography, Topology and Stability of the Magnetospheric Boundary

Let us envisage a cylindrical magnetic flux tube of small cross section totally contained in region I-A (Figure 2). As the solar wind plasma contained in this tube at any given time t moves with bulk velocity $\mathbf{V}$, it will remain in a thin flux tube at any later time $t + \Delta t$, due to the validity of relation (1) ('line-preservation', Newcomb, 1958) in the region occupied by this plasma. This is customarily interpreted by saying that the interplanetary field lines 'move with velocity $\mathbf{V}_\perp$'*, where $\mathbf{V}_\perp$ is the component of $\mathbf{V}$ perpendicular to the local interplanetary magnetic field $\mathbf{B}_i$ (IMF). A less picturesque but perhaps more mature description (Alfvén, 1976a) is to state that the solar wind plasma tube is drifting transversely to the interplanetary field with a velocity $\mathbf{V}_\perp = \mathbf{E}_i \times \mathbf{B}_i / B_i^2$ due to the presence of a convective electric field $\mathbf{E}_i$. The

* There is an infinite family of vectors which are 'line preserving' and which could be used with equal legitimacy to define a field line velocity (Vasyliunas, 1972). What most investigators use (mostly without saying so) is a phenomenological definition of local field line velocity given by the electric drift velocity of a probe charge injected with vanishing kinetic energy in absence of non-electromagnetic forces (Roederer, 1970), or, which is the same, by the instantaneous velocity of a charged particle for which the Lorentz force exactly balances the electric force (Stern, 1977). Note that the component of the bulk velocity parallel to the magnetic field does not appear in the moving field line picture at all. Note also that the moving field line picture loses its 'intuitive simplicity' – and as a matter of fact may become a serious conceptual trap (Alfvén, 1976b) – for all those field lines on which the validity of the MHD approximation (1) *is limited to a finite portion* (as it happens with field lines in all topological regions of Figure 2, except region IV!).

physical sources of $\mathbf{E}_t$ are polarization charges due to the impressed forces acting at the base of the corona (and, possibly, due to equivalent electric charges associated with moving diamagnetic currents and with vortices or discontinuities in the flow). On a global scale, $\mathbf{V}$ is to be considered the 'cause', $\mathbf{E}_t$ the 'effect' in relation (1) for the solar wind (Stern, 1977).

When the plasma flux tube impinges on the bow shock wave, it is kinked in the rotational discontinuity; as it crosses the shock, the plasma is heated. The bulk motion of the flux tube in the magnetosheath will be governed by the particular interaction mechanism between the streaming plasma and the magnetosphere. Since the Earth's magnetosphere is a small obstacle with respect to the macroscopic inhomogeneities of solar wind flow, on the local scale of this interaction it is the convective electric field $\mathbf{E}_t$, mapped down along equipotential magnetic field lines from the unperturbed regions of the solar wind, which is to be considered the externally impressed quantity in the MHD relation (1).

Two extreme cases can be envisaged, between which the real situation of solar wind-magnetosphere interaction may lie.

(1) One extreme situation would be that of a purely gasdynamic flow around a 'closed magnetosphere', with the magnetopause acting as a two-way magnetic shield (tangential discontinuity only; perpendicular component of the magnetic field on the magnetopause $\mathbf{B}_\perp = 0$ everywhere; no field line connection (no region II in Figure 2)). In this case all incoming plasma tubes would swing around the magnetopause, and only an infinitesimally thin slab of plasma would maintain a tangential apposition on the latter at the stagnation point, from there gliding downstream. Diamagnetic currents and electric polarization in the magnetosheath would ensure that the transverse flow velocity is coupled to the magnetic and electric field vectors through relation (1) everywhere in this particular gasdynamic flow. The only way that solar wind plasma could penetrate into the magnetosphere in this extreme case is by diffusion through the magnetopause or by flow into the 'one-dimensional' boundary neutral points that would exist in this closed-magnetosphere configuration. The efficiency of the entry process would depend on the particular diffusion mechanism envisaged, on the magnetosheath plasma distribution function in front of the magnetopause, on the microstructure of the boundary, and on the magnetic field inside.

Note that case (1) would correspond to a hypothetical situation in which $\mathbf{B}_t \to 0$, or to a model in which a magnetized, superalfvénic solar wind flows against a blunt object (the magnetopause) with superconducting properties (to insure $\mathbf{B}_\perp = 0$). The picture of an unmagnetized solar plasma, though far removed from reality, has been used quite successfully in studies of the structure of the magnetopause (see review by Willis, 1975) and in numerical determinations of its shape (see review by Walker, 1976). The second model represents a condition under which the plasma equations decouple into a gasdynamic set (giving the flow configuration) and an electromagnetic set (describing the magnetic field) which can be used to draw up quantitative descriptions of the magnetosheath (see review by Fairfield, 1976).

(2) The other extreme situation would be represented by a magnetopause that acts as a 'one-way boundary', with the interplanetary magnetic field being allowed to penetrate undistorted into the magnetosphere [i.e., where the perpendicular magnetic field component on the magnetopause is equal to that of the unperturbed interplanetary field: $\mathbf{B}_\perp = (\mathbf{B}_t \cdot \mathbf{n})\mathbf{n}$; $\mathbf{n}$: normal to the magnetopause]. This extreme situation would imply an undisturbed flow of magnetosheath plasma right onto the magnetopause (no bow shock!). The resulting field geometry inside the magnetospheric cavity would be given by the linear superposition of the magnetospheric field (of sources on and within the magnetopause) and the (uniform) solar wind field (Forbes and Speiser, 1971). Two model examples are shown in Figures 3a and b (Saunders, 1976), for southward- and northward-directed interplanetary magnetic fields, respectively. The important point is that plasma tubes drifting into the magnetopause will now be 'cut' at points whose position will depend on the direction

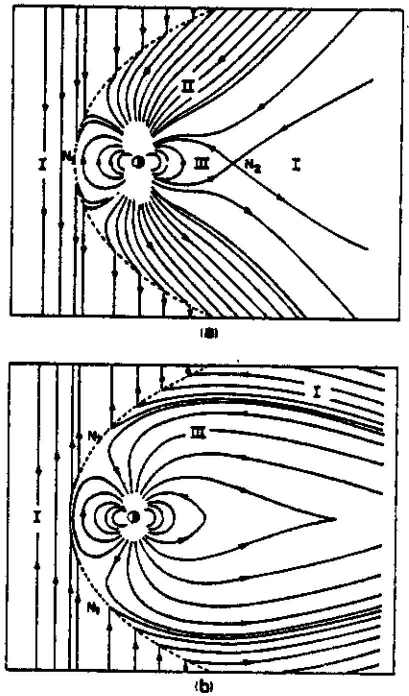

Fig. 3. Two models of magnetic field topology, with the interplanetary magnetic field penetrating undistorted into the magnetosphere (Saunders, 1976). (a): southward interplanetary field; (b): northward field. (*Note*: field lines selected arbitrarily; field line 'density' does not represent flux density).

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of B_i. For an interplanetary field directed due south, these points lie on the equatorial surface (N_1 in Figure 3a). For a northward field there would be two cutting points N_1 located at high latitudes on each meridian (Figure 3b). For a southward-directed field, the incoming solar wind plasma will drift onto and through field lines of class II (Figure 3a), which are connected to the polar cap. Note that here we have a case of plasma flow between regions of different topology (I and II). Solar wind plasma now would be allowed to flow into the magnetosphere everywhere along the magnetopause in region II (the magnetopause would be a wave-like structure). This entry flow would be governed by the particular magnetic field geometry connecting regions B and C (Figure 2), by the plasma distribution function prior to entry, and by the microstructure of the magnetopause (Section 3). A similar plasma tube breaking is bound to occur at point N_2 in Figure 3a, where the plasma is again transferred to different field-topological regions (I and III). In the case of a due northward B_i no region II arises (Figure 3b). The incoming plasma could drift into the closed field line region III at low latitudes (continuity of the tangential component of the electric field across the boundary); at high latitudes, above the breaking points N_1, it would remain on class I field lines which, however, do cross the magnetopause to become part of the distant magnetospheric tail (region I-C in Figure 2).

In this extreme case (2) all plasma tubes projected in the direction of the bulk velocity V onto the magnetopause will be 'broken'. The points at which the intercepted plasma tubes are cut lie on a curve called the 'X-line', Since field lines are equipotentials both outside and inside the magnetosphere (we are implicitly assuming that they are occupied by zero resistivity plasma everywhere in the domain under consideration), whenever a region of class II arises (Figures 2, 3a) the solar wind electric field E_i is mapped right down into the area of the ionosphere intercepted by these field lines (Stern, 1973).* Hence, plasma convection over the polar cap would be directly controlled by the convection of the solar wind (E_i is the 'cause', V the 'effect' in relation (1)). It is important to note that in these models, for field-topological reasons only, the convection over the polar caps turns out to be mainly tailward for nearly *all* directions of the IMF (Stern, 1973; Saunders, 1976).

Finally, yet another extreme configuration could, in principle, be envisaged in which a magnetopause simply does not exist. In this case the magnetic field is a linear superposition of the fields of the solar wind and the planetary body *everywhere* in space. Though representing an even more unrealistic situation than case (2) above, such a superposition also gives rise to field-topological regions of type I, II and III, depending on the relative orientation of the superposed fields, and has been used in quantitative analyses of the geometric features of the resulting field configuration (Stern, 1973; Yeh, 1976).

The real situation of a planetary magnetosphere in steady-state configuration lies somewhere between the extremes (1) and (2), depending on the orientation of the

* The possible breakdown of the MHD approximation (1) in the vicinity of the magnetopause would not invalidate field line equipotentiality, provided the breakdown region along the field line is very thin (Vasyliunas, 1976).

interplanetary magnetic field and on the plasma processes occurring on and near the magnetopause. Incoming solar wind plasma tubes apposing on the magnetospheric boundary will be broken; however, the efficiency of this process (total intercepted flux) and that of solar wind penetration into the magnetosphere will be controlled by the fine-structure of the boundary and that of the magnetosheath plasma. Whatever boundary current system results, the actual magnetic field topology *inside* the magnetosphere and its connection with the interplanetary field will be determined by the actual distribution of the normal component $B_\perp$ on the magnetopause. In a steady-state situation this represents a conceptually simple magnetostatic problem (Voigt, 1976). An obvious but often neglected fact is that the distribution of the normal component $B_\perp$ on the magnetopause – even a very weak one – will necessarily affect the configuration of the magnetic field in the tail and all its topological features such as neutral lines (see Section 4). It is important to point out that the actual position and shape of the boundary and the magnetic field configuration adjacent to it are the result of *all* currents in the magnetospheric system, proximate *as well as distant*.

The experimental determination and theoretical description of how the magnetic field in the magnetosheath and the structure and shape of the magnetopause influence each other might well be called today's 'task number one' of magnetospheric plasma physics. It is necessary to identify what properties of the magnetosphere are generated, and what properties are only modulated, by the interplanetary magnetic field. In particular, it is necessary to determine whether a unique steady-state configuration of the system of Figure 2 exists and what the magnetic field topology on and near the magnetopause is for a given IMF direction; whether the actual steady state depends on the history of the system (i.e., on how B_i was set up), and whether there are conditions for which instabilities make a steady-state situation outright impossible.

For instance, a conspicuous place where a disruptive instability might occur is at those points of the X-line on the boundary on which the local magnetic field vanishes. In the neighborhood of such points (X-type neutral points, N_1 in Figures 2 and 3a) the MHD approximation and isotropic fluid description break down; a solar wind plasma tube drifting into such a region (which requires an appropriate local electric field) will not only be cut, but, for the portion of the plasma flowing into the breakdown region, the individuality as pertaining to a given plasma tube will be lost. The question arises whether under such circumstances a steady-state regime can exist at all, i.e., whether the general magnetic field configuration can be maintained without change, or whether the plasma flow into the neutral point region will entice a temporal change in boundary configuration between the field-topological regions I and II such that the total magnetic flux in region II is changed (for instance, increased). Note carefully that, necessarily, region III would also become involved in such a flux transfer process: any total magnetic flux increase of region II must occur at the expense of a decrease of flux in region III (this has been called 'erosion' of the closed field line region III on the dayside). Also the plasma (if any) in region III will necessarily be involved. Indeed, since there is a flow into the neutral point in medium I caused by the convective electric field $\mathbf{E}_t$, continuity of the tangential component of the electric field requires that the plasma of region III (where the magnetic field is reversed) also flow into the neutral point (and that plasma flow away from it in region II).

The terms 'magnetic merging' and 'reconnection' have been chosen to designate a plasma transfer across the 'separatrix' surface defined by field lines passing through an X-line into a region of different field topology (Vasyliunas, 1976). Such a transfer process necessarily implies the existence of a macroscopic electric field in the region of the X-line, directed along the latter, responsible for the plasma flow into and out of the region. It also implies the breakdown of the MHD approximation in the vicinity of the neutral points on the X-line because of $B \to 0$. Reconnection is a plasma-dynamic process in which field energy is converted into particle energy. But it is more than that (*any* region in which $\mathbf{j} \cdot \mathbf{E} > 0$ has this property). What counts in a merging or reconnection process are *the feedback effects of MHD breakdown and associated turbulence and shocks on the entire macroscopic plasma flow and electromagnetic field configuration.* (For a discussion of the processes in the breakdown region and their local effects, see reviews by Vasyliunas (1975) and Sonnerup (1976a)). In the present article, the term field line 'connection' or 'interconnection' will be reserved to merely describe the topological feature of field lines crossing the magnetospheric boundary ($\mathbf{B}_\perp \neq 0$, Region II, Figure 2) (Roederer, 1973). It does not necessarily imply the occurrence of a plasma-dynamical process as described above. For instance, in a vacuum field we may have interconnection but not reconnection; in a plasma, there are conditions under which we may create an X-line by manipulating *external* currents and regulate the plasma transfer through the separatrix by manipulating an electric field of *external* sources, without the appearance of this X-line and associated MHD breakdown in any way causing a transition into a new plasma-field configuration. Most unfortunately, in the literature the terms reconnection and merging are frequently used to merely designate the topological feature of field line connection across the magnetopause (open magnetosphere). Note that the existence of an X-line on the boundary of an 'open magnetosphere' interconnected with the interplanetary magnetic field, though a necessary, is by no means a sufficient condition for the occurrence of a large-scale semistationary magnetic merging process as defined above.

One of the most serious hurdles in the approach to 'task No. 1' lies in the difficulty of obtaining experimental information on the magnetic field configuration adjacent to and across the magnetopause. Very high sampling rates are necessary to provide enough data prior to, during, and after the few seconds of satellite traversal time through the relevant region. Simultaneous measurements of all major plasma parameters are required. Single satellite observations make it difficult to separate spatial from temporal effects and to determine the local orientation of the boundary, which must be known in order to be able to determine $\mathbf{B}_\perp$, i.e., the field line connection topology. Last but not least, global information on the integral state of

the magnetosphere as well as on the parameters of the incident undisturbed solar wind is needed to distinguish between boundary features governed by local processes and features which represent an integral response to distant conditions.

In spite of these difficulties some concrete results have been achieved in recent years. Measurements indicate that the magnetic field in the magnetosheath near the magnetopause surface is preponderantly parallel to the latter (e.g., Paschmann *et al.*, 1976; review by Fairfield, 1976), indicating that the gasdynamic 'extreme' (1) described above may not be too far removed from reality (which comes as a surprise when considering a collisionless plasma (Heikkila, 1973)). These observations, however, do not preclude the existence of a small perpendicular component $\mathbf{B}_\perp$ across the magnetopause. Indeed, some magnetopause crossings can be interpreted in terms of a rotational discontinuity (e.g., Sonnerup and Ledley, 1974); these events, however, seem to be rare. Quite generally, the experimental evidence of field line interconnection between the magnetosphere and the solar wind so far is only indirect, sometimes rather inconclusive, or based on the analysis of single events. It is indeed fair to say that evidence for an 'open' magnetosphere is mainly based on observations for which such a model offers the simplest (but not always unique) explanation requiring a minimum number of assumptions. For instance, the principal features of solar particle access and distribution over the polar caps can be explained quite convincingly by assuming that regardless of IMF direction there is a direct connection between geomagnetic and interplanetary magnetic field lines, with the region of connection lying within a few hundred earth radii in the magnetospheric tail (e.g., review by Paulikas, 1974; Meng and Kroehl, 1977). Observations of lunar absorption effects on solar electrons in the tail (Anderson and Lin, 1969) point to the existence of field lines of class II (Figure 2). Yet, although there is a clear correlation of the north-south asymmetry of the solar particle flux in the polar caps with the azimuthal direction of the interplanetary field, other predicted features such as day-to-night development pattern of particle influx (Michel and Dessler, 1975) have not been observed. Even some features of solar proton entry can be adequately explained by particle orbit integration across the tangential discontinuity of a closed magnetosphere boundary (Morfill and Quenby, 1971; Durney *et al.*, 1972). On the other hand, observed correlations between interplanetary field direction and geomagnetic variations in, and the size of, the polar caps (e.g., Svaalgard, 1973; Akasofu *et al.*, 1973a), or the configuration of the polar cap electric field (e.g., Heppner, 1973; Mozer *et al.*, 1974) have been invoked as evidence for a topological interconnection between magnetospheric and interplanetary field lines.

Turning to the plasma-dynamical process of merging or reconnection on the boundary, plasma observations near the magnetopause have so far failed to confirm the characteristic flow that should be expected if a reconnection process were to take place on the dayside magnetopause on occasions of 'favorable' field configurations (Paschmann *et al.*, 1976). The absence of such a flow seems to argue against a local merging process being the source of large-scale laminar effects, but not necessarily against the topological interconnection of magnetospheric and interplanetary fields.

There are, however, effects that have been interpreted in terms of a merging process on the dayside magnetopause. The existence of a layer of field-aligned, antisunward-streaming energetic electrons in the magnetosheath within about $3R_e$ of the magnetopause (Meng and Anderson, 1970, 1975; Domingo *et al.*, 1974; Baker and Stone, 1977a) has been considered to be evidence for a merging process at the nose or the cusp of the magnetosphere (Axford, 1976). Another effect is the gradual increase in magnetic field intensity in the tail lobes that occurs during periods of sustained southward-directed $\mathbf{B}_t$ (e.g., review by Burch, 1974). This effect may not be due to a compression of the tail lobes; indeed, the tail radius has been reported to increase (Maezawa, 1975). (The associated decrease in tail plasma pressure required by pressure balance considerations so far has not been detected.) Here we have a situation in which an essentially 'static' input configuration (the southward interplanetary field) leads to a dynamic response in the magnetosphere ($\partial B/\partial t > 0$ in the tail). Another effect is represented by the observation of more earthward dayside magnetopause positions in association with southward-directed interplanetary fields (Fairfield, 1971) (this effect being strongly washed out by variations in solar wind pressure) and by the fact that geomagnetic substorms are more likely to be detected by the existing chain of geomagnetic observatories during such periods of time (Akasofu *et al.*, 1973a) (because of an increased size of the polar cap region during times of southward-directed IMF). The fourth effect frequently quoted as an indication for merging on the dayside magnetopause is one example in which a large inward motion of the dayside boundary was observed during a time of constant solar wind kinetic enegy flux (Aubry *et al.*, 1970). Finally, in a few cases of spacecraft traversals of the magnetopause near the subsolar point, magnetic field signatures have indeed been found that strongly point to an X-line configuration (Sonnerup, 1977).

However, alternate descriptions of some of these effects can be given that do not require anything 'special' happening on the dayside boundary except for the appearance of a particular distribution of $\mathbf{B}_\perp$, i.e., a particular interconnection topology, and/or that only invoke internal mechanisms operating inside the tail (the plasmasheet). In Section 4 we shall describe such an alternative to explain the second abovementioned effect of tail field intensity increase. The third and fourth effects mentioned above, too, need not be interpreted as originating in a plasma-dynamical merging process localized at the nose of the magnetopause. They could represent an integral field reconfiguration due to the increase (and earthward displacement) of the cross-tail current sheet (e.g., Unti and Atkinson, 1968), caused by an enhanced plasma convection into the tail during times of southward IMF. (To explain the large inward motion of the boundary mentioned in the preceding paragraph, the required tail current increase seems to be rather high (Russell *et al.*, 1974); however, there are enough uncertainties in this event (e.g., in the actual direction of the normal to the magnetopause) that a field-geometric explanation could not be ruled out.) Finally, certain features of the energetic electron layer in the magnetosheath, such as its permanent nature, its latitude- and longitude-independent structure and spectrum,

and the rather weak correlation of electron flux with the direction of the IMF (Meng and Anderson, 1975), are rather difficult to reconcile with the assumption that this layer originates in a merging process at the front of the magnetopause, for in such a case the spatial location of the layer's source region – the X-line – would have to depend very strongly on the direction of the IMF*. Finally, unless reconfirmed with simultaneous plasma measurements, the appearance of an X-line configuration of the magnetic field on the boundary should not be taken as evidence of a merging process with large-scale effects on the magnetospheric system.

3. Problem No. 2: The Mechanisms for the Entry of Solar Wind Plasma into the Magnetosphere

So far we have dealt mostly with magnetic field aspects of the solar wind interaction with the magnetosphere. This interaction, however, also controls the intrinsic, microscopic structure of the magnetospheric boundary, and it regulates the motion and energy dissipation of magnetosheath plasma during the process of its entry into the magnetosphere proper. The plasma structures under consideration here are the magnetopause, from now on to be considered a layer of small but finite thickness, and the plasma layers known as the low-latitude boundary layer, the entry layer, the 'throat', the cleft or cusp, the mantle, and the magnetotail boundary layer, sketched in Figure 4. A study of these boundary layers is of particular importance because they involve dynamical phenomena that are unique to plasma flow *interfaces* and do not occur in the more uniform portions of the solar wind sectors and inside the magnetospheric plasma 'reservoirs' such as the plasmasheet and plasmasphere (Figure 4).

The magnetopause layer can be defined as the region where the currents flow that cause a more or less abrupt change in the magnetic field and plasma configuration, separating magnetosheath from magnetosphere (see reviews by Willis, 1975, 1977; and Sonnerup, 1976a). The predicted thickness of this layer lies anywhere between the average solar wind proton gyroradius in the boundary's magnetic field down to the plasma skin depth (geometric mean of average proton and electron gyroradii). As magnetosheath particles impinge on the confined magnetic field, they are deflected transversally to the **B** vector in opposite senses; this transverse motion represents the *Chapman-Ferraro current* (Ferraro, 1952). The Lorentz forces acting on this current system furnish the force system needed to equilibrate the dynamic plasma pressure of the impinging solar wind. The actual structure of this current layer depends on whether the electric polarization field created by the ensuing electron and ion charge separation (difference in turning points) is neutralized totally or partially by the

* In the minds of many magnetospheric physicists, a 'southward directed IMF' is pictured as pointing *due* southward (Dungey, 1961). Such a situation, however, is very rare (Fairfield, private communication). Thus, a field configuration as shown in Figure 3a, with the X-line lying on the equator in its entirety, is an exception. An IMF that is just tipped southward is expected to engender an X-line meandering on the boundary at widely varying latitudes.

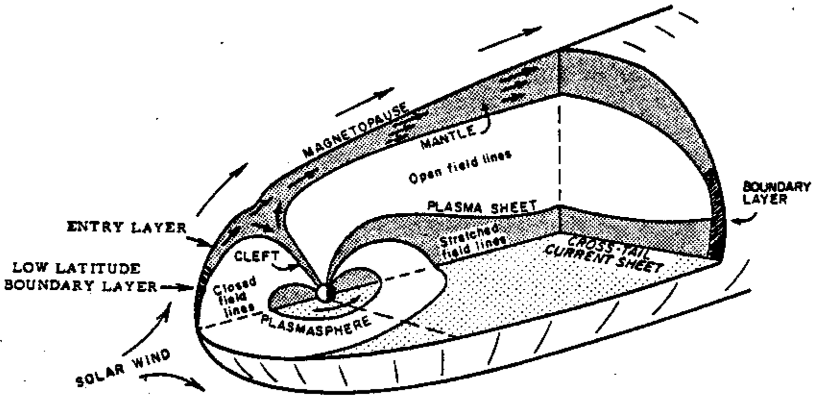

Fig. 4. Sketch of fundamental plasma regions in the magnetosphere.

ambient plasma. If this electric field is completely neutralized, the impinging magnetosheath ion and electron streams move independently of each other and every particle penetrates into the geomagnetic field a distance approximately equal to its gyroradius in the average magnetic field within the boundary layer (~100 km for protons). If it is not neutralized at all, the average thickness of the magnetopause would be reduced to the plasma skin depth (~1 km). Neutralization should be possible if thermal particles are drawn up along magnetic field lines from the ionosphere to the boundary. The time-scale for this process (hours), however, is considerably longer than that of usual time-variations of solar wind parameters. Rapid diffusion of solar wind particles across magnetic field lines in the magnetopause layer would be another mechanism to neutralize the electrostatic field.

The actual microstructure of the magnetopause and its equilibrium are expected to depend on the angle between the magnetosheath bulk flow velocity **V** adjacent to the boundary and the magnetospheric field **B** immediately behind the magnetopause (Figure 5). In one view (Parker, 1967) no static equilibrium should be possible if **V** has a component parallel to the confined magnetospheric field. In such case, two field-aligned ion and electron current sheets would appear in the magnetopause layer, generating an extra magnetic field transverse to the magnetospheric field. The Lorentz force due to this extra field acting on the ion current sheet would oppose the solar wind pressure-balancing Lorentz force on the main Chapman-Ferraro ion current in the confined magnetospheric field. The resulting lack of equilibrium should be a small-scale effect, leading to enhanced mixing between magnetosheath plasma and magnetospheric plasma and associated momentum transfer to the latter. However, other studies (e.g., Davies, 1969) indicate that the effect of this extra magnetic field should depend on the degree of electric field neutralization in the boundary and that equilibrium would be upheld in any case. None of the theoretical

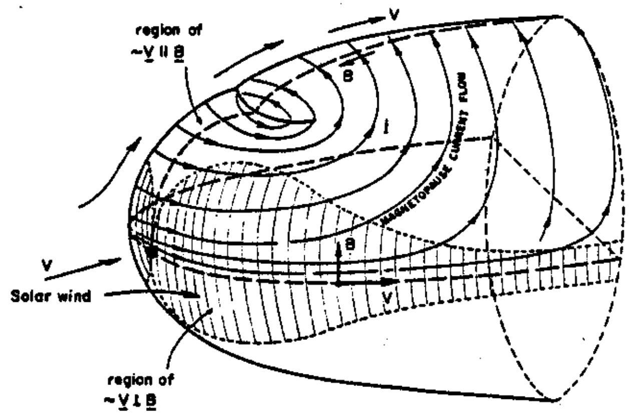

Fig. 5. Sketch of magnetopause currents **j** in relation to magnetosheath plasma flow **V** and confined magnetic field direction **B**.

studies of intrinsic stability of the magnetopause takes into account the effects of a possible perpendicular component of the magnetic field $\mathbf{B}_\perp$ (interconnection topology, Section 2).

Even a steady-state boundary layer should be susceptible to micro-instabilities. For instance, streaming of magnetosheath plasma through the ambient plasma in the boundary layer would generate a two-stream ion-cyclotron instability (Eviatar and Wolf, 1968), with the result of strong proton scattering and associated momentum and particle transfer to the magnetosphere. An electron-cyclotron instability would be responsible for electron scattering (Alpers, 1971). Recently, attention has been called (Haerendel, 1977) to the possible effects on the magnetopause and particle transfer through it of an eddy turbulent flow in the vicinity of the cusp indentations (demarcation lines, Figure 5). It is conceivable that such perturbations may well lead to limited-scale, short-term, nonlaminar merging events on the high latitude magnetopause (Haerendel *et al.*, 1977).

On a larger scale-size, shock waves impinging on the magnetopause from the magnetosheath should cause local deformations and surface waves on the boundary. More significantly, attention was called recently (Lemaire and Roth, 1976) to the fact that even a steady-state solar wind flow consists of intertwined filamentary plasma elements (e.g., Siscoe *et al.*, 1968; Turner *et al.*, 1976), and that the excess momentum of these field-aligned inhomogeneities (of transverse scale size of $1R_e$ or less) should cause dents and ripples on the magnetopause. Moreover, it is conceivable that in view of this filamentary structure of the solar wind, the normal component $\mathbf{B}_\perp$, the associated field interconnection topology, the stability of the boundary, and the particle and momentum transfer may all be non-uniformly distributed over the magnetopause, which even for a quiet solar wind condition might have a 'patchy' structure, with elongated 'pockmarks' and 'blisters'. This patchy structure would map right down onto the polar caps along the interconnected flux tubes, and there would be no single separation boundary between 'open' and 'closed' field lines. In such a situation it would be impossible to predict which tail field lines will be 'open' (interconnected) and which will be closed. Finally, in view of the tilt of the earth's geomagnetic axis with respect to the rotation axis, the diurnal rotation of the internal field sources is expected to cause a seasonally modulated diurnal shift of the magnetopause current system around the demarcation lines (Figure 5) and, to a small extent, a diurnal variation of the shape of the boundary surface (e.g., Olson, 1969).

For a closed magnetosphere in a steady state ($\mathbf{B}_\perp = 0$) it is difficult to ascertain whether or not the magnetopause should be an electrostatic equipotential surface. Indeed, this would depend on whether it is made up of a bundle of field lines converging into a single neutral *point* on each 'hemisphere' (Figure 6a) as most numerical models predict, or whether the boundary field lines converge into a demarcation *line* and intersect the ionosphere along a line of finite length (Figure 6b). If the boundary were an equipotential, there could be no dissipation or generation of electromagnetic energy by the magnetopause currents. In a steady state, transfer of energy, momentum and particles from the magnetosheath plasma to the magnetosphere would be possible only via diffusion mechanisms or instabilities in the boundary layer (see below).

This situation changes dramatically, however, if field line interconnection through the boundary is allowed. First, in such a case the Lorentz force on the boundary currents will have a component parallel to the boundary serving to accelerate (deflect) the plasma that is penetrating into the magnetosphere. Second, the impressed interplanetary electric field, as observed in a system fixed to the magnetosphere, is mapped onto the boundary along the equipotential magnetic field lines (p. 30). For a southward interplanetary magnetic field, for instance, the situation of Figure 6c would arise. In a region where $\mathbf{j} \cdot \mathbf{E} > 0$ (nose and dayside magnetopause equatorward of the demarcation line), dissipation of electromagnetic energy takes place (the magnetopause acts as a 'load'); magnetopause regions where $\mathbf{j} \cdot \mathbf{E} < 0$ (tailward of the cusp or demarcation line) act as a generator. The magnetopause current system becomes 'active'; in order to maintain it in steady state, kinetic energy (ordered or thermal) has to be withdrawn from the dayside magnetopause, whereas kinetic energy has to be supplied to the tail magnetopause. In the consideration of Figure 6c it is necessary to include the cross-tail current sheet (sometimes inappropriately called 'neutral sheet'), because it merges into the boundary current system at the flanks (the surface divergence is $\neq 0$ there). An electric field as shown in Figure 6c thus also leads to $\mathbf{j} \cdot \mathbf{E} > 0$ in the cross-tail current sheet.

It is important to point out here that, in view of the fact that the magnetopause does not seem to suffer any 'zeroth-order' changes as a result of a change in the IMF, the electric field component tangent to the boundary must be totally incidental to the mechanism that maintains the boundary current in operation (Heikkila and Pellinen, 1977). Thus, the (kinetic) energy generated in $\mathbf{j} \cdot \mathbf{E} > 0$ regions must ultimately be

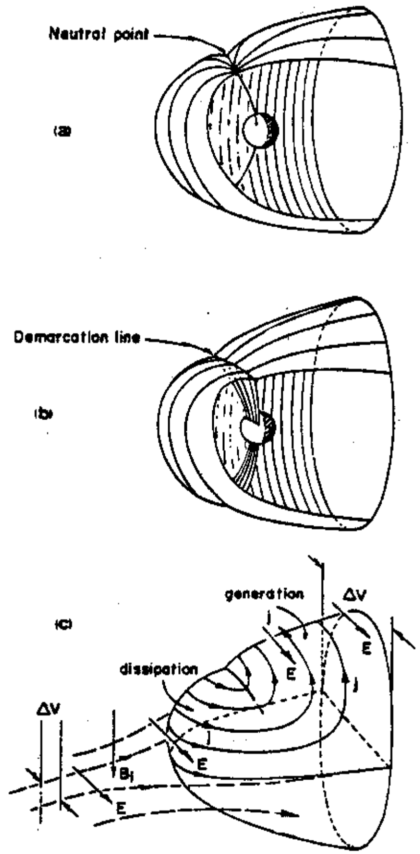

Fig. 6. (a) and (b): possible magnetopause field line geometries in a closed magnetosphere model. (c): open magnetosphere with southward IMF; the convection electric field $\mathbf{E}$ in relation to magnetopause currents $\mathbf{j}$ is shown. ΔV: potential difference across the magnetosphere (and polar cap).

provided by the generator which maintains the electric field (in the distant solar wind); likewise, the (electromagnetic) energy generated in $\mathbf{j} \cdot \mathbf{E} < 0$ regions must be provided by the local flow (kinetic energy of the magnetosheath).

On a patch of boundary on which $\mathbf{B}_\perp \neq 0$, two alternatives are possible, depending on the field topology. Figure 7a corresponds to the case of dayside magnetopause equatorward of the demarcation line with (interconnected) southward-directed IMF (steady state assumed). Note that $\mathbf{j} \cdot \mathbf{E} > 0$, the Poynting vector (parallel to $\mathbf{V}_\perp$) pointing toward the current sheet from both sides, energy being delivered to the

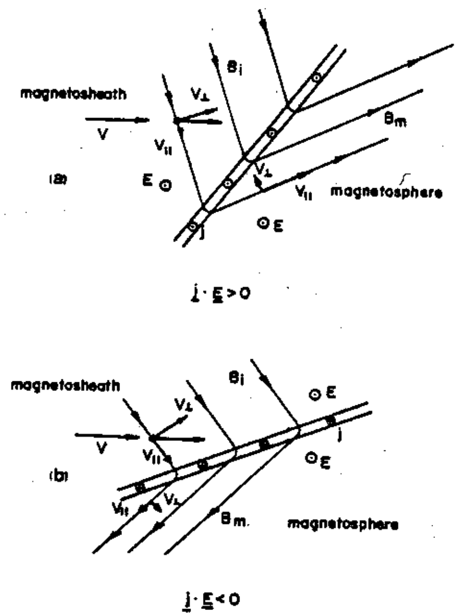

Fig. 7. Alternatives for field topology on magnetopause with $\mathbf{B}_\perp \neq 0$ (southward IMF assumed). (a): dayside magnetopause equatorward of cleft; (b) tailward of cleft. Anyone fond of the 'moving field line picture' would 'see' the field lines collapse from both sides into the boundary with velocity $\mathbf{V}_\perp$ in case a, generating mechanical power at the rate $\mathbf{j} \cdot \mathbf{E}(>0)$; or emerge out of the boundary toward both sides in case b, generating electromagnetic power at the rate $\mathbf{j} \cdot \mathbf{E}(<0)$.

current carriers, and plasma flowing from the magnetosheath into the magnetosphere along field lines (in principle, also a reverse flow would be possible). Whether the generated kinetic energy appears in random form and/or as an organized flow enhancement will depend on the fine-structure of the boundary current layer and on the microinstabilities therein; these factors will also control the plasma entry process and the associated change in particle distribution function. It has been pointed out (Heikkila, 1975) that if the total dayside magnetopause current ($\sim 9 \times 10^6$ A) flows through the average magnetospheric dawn-to-dusk potential difference (~ 60 kV), the total power dissipation would be about 5×10^{11} W. Any lack of experimental confirmation of this power dissipation would necessarily imply that $\mathbf{B}_\perp \simeq 0$ on the boundary (or $\mathbf{E} \simeq 0$ – although this latter condition would mean zero transverse flow $\mathbf{V}_\perp$ in the magnetosheath near the magnetopause (Figure 7), a most unrealistic situation when $\mathbf{B}_\perp \neq 0$). The energetic electron layer observed in the magnetosheath adjacent to the magnetopause (p. 33) could well carry an important part of this power (Baker and Stone, 1977a). Note that the electromagnetic energy dissipation on the

boundary in the case of Figure 7a does not require the existence of a neutral point in the immediate neighborhood, nor does it imply the operation of a plasma-dynamical merging process as described on p. 32.* On the other hand, it has been suggested (Paschmann *et al.*, 1976) that on the higher latitude dayside magnetosphere this kind of boundary could represent a standing Alfvén wave (rotational discontinuity) that originates in a merging process at an X-line (Levy *et al.*, 1964).

Figure 7b portrays the other alternative, as it would apply to the magnetopause for an interconnected southward IMF, tailward of the demarcation line. This represents a source of electromagnetic energy ($\mathbf{j} \cdot \mathbf{E} < 0$), with the Poynting vector directed away from the magnetopause on both sides, and field lines 'seen' to emerge from it. The generated field energy must be provided by the mechanism that maintains the boundary current system (the magnetosheath flow).

In both cases of Figure 7, a diversion of the boundary current along field lines into the ionosphere will irreversibly disturb the plasma equilibrium across the boundary. A macroscopic instability would set in, leading to macroscopic changes in the shape of the boundary that would depend on the plasma properties on both sides of the magnetopause (Coroniti and Kennel, 1973). At present, no theory exists for boundaries with $\mathbf{B}_\perp \neq 0$ of width comparable to the ion gyroradius (Sonnerup, 1976b). The proper inclusion of the IMF requires that a realistic quantitative theory of the microstructure of the magnetopause would have to be based on the kinetic theory of anisotropic plasmas (Willis, 1977).

Returning to the case of a closed magnetosphere, or, more generally, to the low-latitude region of the magnetopause where the magnetosheath flow is nearly perpendicular to the confined magnetic field behind the boundary (Figure 5), yet another mode of particle penetration has been proposed. Under certain conditions of field gradient inside the magnetosphere (Cole, 1974), impinging solar wind particles could be drift-captured, i.e., would drift away from the boundary before they have completed the first cyclotron turn inside the magnetosphere. This process would work preferentially for particles whose cyclotron radii are considerably larger than the magnetopause thickness (i.e., particles belonging to the upper end of the thermal spectrum in the magnetosheath).

In general, whenever there is a bulk flow of boundary plasma perpendicular to the confined magnetospheric field impressed by some momentum transfer or viscous

* Of course, for field-topological reasons an X-line *must* exist somewhere on the boundary for a situation like that in Figure 7a. But its existence is not at all necessary for the conversion of magnetic field energy into kinetic energy, even in a steady-state case: just note that in Figure 7a the zeroth order drift velocity $\mathbf{V}_\perp = \mathbf{E} \times \mathbf{B}/B^2$ is always parallel to the Poynting vector and directed *into* the current sheet. Those fond of the moving field line picture should thus look at these lines as 'merging' or 'collapsing' into the current sheet from *both* sides of the boundary with velocity $\mathbf{V}_\perp$ – well away from any X-line (of course, the plasma also has a parallel velocity $\mathbf{V}_\parallel$ which completely escapes the 'frozen field' description, but which is the one to be affected (with the temperature) during the entry process by microscopic dynamic processes in the magnetopause layer; to consider that each kinked field line shown in Figure 7 is moving 'rigidly' to the upper right, parallel to the boundary, physically does not make any sense, for such a statement would imply a non-existent constraint on $\mathbf{V}_\parallel$).

interaction mechanism, electric polarization will occur and a dynamo electric field will build up in the flow layer (Cole, 1976; see also Section 5). Due to ionospheric conductivity, this polarization will lead to an electric field inside of the boundary layer that on the equatorial plane is directed from dawn to dusk, if the magnetopause is an equipotential surface and no electric fields parallel to **B** exist (Mendillo and Papagiannis, 1971). In other words, a dawn-dusk electric field can exist even in the absence of field line interconnection. Note that cancellation of this permanent dawn-dusk electric field would require an impressed field of external (e.g., solar wind) origin directed from dusk to dawn. A polarized boundary layer represents a momentum transfer region (Piddington, 1960; Eastman *et al.*, 1976) in which the efficiency of the transfer mechanism is controlled by the degree of leakage of the polarization charges out of the layer (see also Section 5).

The existence of plasma layers beneath the magnetopause proper, representing 'freshly injected' magnetosheath particles, has been postulated since the inception of magnetospheric research. But theory has been unable to make many quantitative predictions – for instance, the distinct variety of circumboundary regions (Figure 4) had not even been suspected until they were discovered experimentally. We have chosen as 'task number two' of magnetospheric plasma physics the experimental determination and the achievement of a quantitative theoretical understanding of the microstructure of the magnetopause, of the entry mechanism of solar wind plasma, and of the dynamic behavior of this plasma immediately after its entry. Evidently there is a great degree of overlap with 'task number one' (Section 3), and the associated experimental difficulties are identical to the ones described on p. 33; for better clarity, however, we preferred to keep the field-topological aspects separated from plasma-dynamic aspects. A major theoretical difficulty is the fact that none of the three problems – the microstructure of the magnetopause, the plasma entry mechanism, or the dynamic behavior of the plasma after entry – can be treated in isolation.

Nevertheless, some concrete results have been achieved in recent years. The magnetopause reveals itself as a complicated boundary, exhibiting many different forms at different encounters (e.g., Neugebauer *et al.*, 1974; review by Willis, 1975). The thickness of the boundary often depends on whether a change in magnetic field magnitude, direction, field fluctuations, or ion flux is considered as the relevant signature. Generally, the observed value is of the order of an average ion cyclotron radius (but sometimes appreciably greater), indicating that effective neutralization of the polarization electric field takes place (p. 36). Magnetic field fluctuations in the frequency range around 0.5 hz were observed in some cases, confirming the predicted ion-cyclotron instability (p. 37). In general, field and particle observations are consistent with the continuity of total pressure across the magnetopause. More recent observations in the high-latitude dayside magnetopause region (Paschmann *et al.*, 1976) have revealed strong diamagnetic effects in the magnetosheath plasma near the boundary leading to strong depressions of the field intensity, which, however, did not bear any other neutral point signatures. They might be an

indication of the incidence upon the boundary of solar wind flux tube inhomogeneities as mentioned on p. 37.

The entry layer (Figure 4) is thought to be a consequence of the entry of magnetosheath plasma through the dayside magnetopause and, partly, of the adiabatic reflection of this plasma in the low-altitude cleft (Paschmann *et al.*, 1976). The field lines in this layer seem to be closed, as evidenced by the existence of trapped energetic particles throughout. The entry layer consists of field-aligned streaming of plasma of density and temperature nearly the same as in the magnetosheath, but with reduced flow speed. Both the thickness of this layer and the plasma content increase gradually from zero at the subsolar point to the cusp latitude (about 78°). When the layer is fully developed, thickness and plasma content appear to be independent of the IMF (Sckopke *et al.*, 1976a). All these facts point against the possibility that the entry layer is the result of a large-scale merging process occurring at the front-side of the magnetopause. Streaming in the entry layer is irregular, at time turbulent, and can be directed away from or toward the sun. The field discontinuity which separates the entry layer from the magnetosheath is the seat of mechanisms which severely alter the plasma distribution function in velocity space. In other words, the magnetosheath plasma has easy but not free access to the entry layer. The density profile of this layer, which exhibits a rather well-defined inner boundary, suggests an entry mechanism based on coherent flow rather than overall diffusion. This, however, should not rule out diffusive transfer through the magnetopause proper at the initial stage of entry. Probably *two* kinds of mechanisms are operative (Reiff *et al.*, 1977). The occurrence of sunward flows has been explained on the basis of magnetic

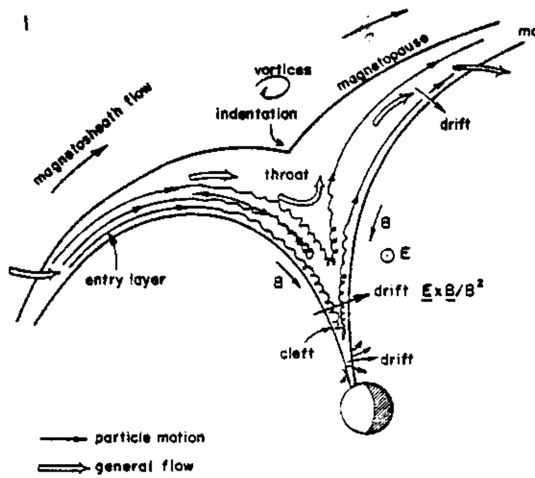

Fig. 8. Sketch of particle motion and plasma flow into and out from the cleft region (not in scale!).

mirroring of entry layer particles as they spiral into the cleft (Figure 8). Most recently (Haerendel *et al.*, 1977), a distinction has been made between the entry layer proper located above 50° magnetospheric latitude and a 'low latitude boundary layer' (Figure 4). This low latitude layer has a more erratic behavior, with a thickness that is negatively correlated with the southward component of the IMF. Flow speeds in this layer are persistently lower than those in the adjacent magnetosheath.

The cusp or cleft is a longitudinally elongated region of intense low-energy charged particle fluxes, composed of entry layer plasma that is approaching the earth's ionosphere; of return streaming of these particles after they have mirrored or have been backscattered; and of upward streaming particles of ionospheric origin. Since its discovery, (Heikkila and Winningham, 1971; Frank and Askerson, 1971), the cusp has been considered a fascinating 'plasma laboratory' where a great variety of phenomena such as plasma instabilities, emissions, wave-particle interactions, turbulence, and field-aligned currents and electric fields can be studied in situ, almost in isolation from the rest of the magnetosphere-ionosphere system (e.g., review by Vasyliunas, 1974). Near the magnetospheric boundary, the region under consideration seems to bear an oval cross-section (marked 'throat' in Figure 8), more restricted in local time extension than the plasma 'cleft' observed at lower altitudes, where it intersects the ionosphere (e.g., review by Haerendel, 1976). The outer boundary of the 'throat' is the magnetopause, which exhibits a clear indentation in this area (Figure 8) (Sckopke *et al.*, 1976a) with interesting vortex signatures in the magnetosheath flow. There are indications, mainly stemming from trapped energetic particle observations (e.g., McDiarmid *et al.*, 1976), that on the sunward side the field lines of the cusp are closed and project into the entry layer, whereas tailward they are open and define the plasma mantle (Figure 8). The broadening in local time or longitude as the cusp or cleft reaches down into the ionosphere may be due to plasma drifts away from the noon meridian caused by the particular configuration of the large-scale electric field in that region (Heelis *et al.*, 1976). These observations also point to an essentially equipotential ($E_\parallel = 0$) dayside magnetopause. In general, it is believed that the cusps or clefts are plasma features rather than magnetic field line features of the magnetosphere. A cusp signature has also been identified in laboratory plasma simulations of the magnetosphere (Podgorny and Dubinin, 1974).

The high-latitude large-scale electric field seems to be the principal organizing and modulating agent of the otherwise highly variable plasma behavior found in the cleft. This field, generally directed from dawn-to-dusk in the vicinity of the noon meridian, imposes a tailward drift on the down-flowing entry layer particles. Although an independent particle description may seem rather unrealistic under cleft conditions, it does explain qualitatively many observed features (Rosenbauer *et al.*, 1975): the softening of proton spectra when the cleft is traversed in poleward direction; the flow and temperature profile of incoming particles that mirror and then 'expand' along the open field line into the mantle (Figure 8); and the observed correlation of mantle thickness with the southward component of the IMF (see below).

Another most relevant characteristic of the cleft is the detection, at low altitudes, of impulsive plasma injections with a well-defined velocity dispersion (Carlson *et al.*, 1976). The source locations were extimated at 10–12 R_e, indeed most presumably on the dayside magnetopause. Impulsive entry of magnetosheath plasma may point again to a non-uniform impact of solar wind inhomogeneities on the dayside boundary or to the effects of eddy turbulent flows (p. 38).

Finally, the role of the ionosphere as a source of cleft plasma is now well established with O^+ ions inferred to flow from the cleft into the mantle (Shelley *et al.*, 1976). Strong field-aligned acceleration must be postulated to explain the high velocities of these ions, probably caused by parallel electric fields in regions of anomalous resistivity (see also Section 5).

The plasma mantle (Figure 4) is a persistent layer of field-aligned tailward flow of magnetosheath-like plasma inside and adjacent to the magnetopause, tailward of the cusp (Rosenbauer *et al.*, 1975). Its thickness at the high-latitude 'top' of the magnetosphere varies between zero and more than 4 R_e, in positive correlation with the southward component of the IMF (Sckopke *et al.*, 1976b). It tapers off from the tail's 'top' toward lower latitudes, where it becomes what was originally called the boundary layer (Hones *et al.*, 1972). The flow speed in the mantle is less than the concurrent flow speed in the magnetosheath, and is positively correlated with the latter. The particle density, temperature and bulk speed decrease gradually with depth from the magnetopause to the inner boundary of the mantle.

These latter features, and the occasional appearance of a plasma 'gap' between the mantle and the magnetopause point against the possibility that the mantle consists of magnetosheath plasma *locally* diffused through the boundary. A more plausible mechanism is the outward expansion of cleft plasma that has been convected onto open field lines by a dawn-dusk electric field (Rosenbauer *et al.*, 1975). Indeed, according to this picture (see also Figure 8), the limited size of the 'source' (the cleft) will automatically limit the thickness of the mantle, which thus will be controlled by the convection speed, i.e., by the convection electric field. Since the latter is correlated to the southward component of the IMF (e.g., Mozer *et al.*, 1974), this field will exert a control on mantle thickness. Slower particles will spend a longer time in the cleft during reflection and thus be convected farther poleward; consequently, bulk speed and temperature will decrease toward the inner edge of the mantle threaded by these more poleward-rooted field lines (Figure 8). Likewise, particles which spiral the largest distance down a cleft field line, i.e., which have the smallest pitch angles in the entry layer, will be convected farther poleward; consequently also particle density will decrease toward the inner boundary of the mantle.

An additional important consequence of this proposed mechanism is that a dawn-dusk convection electric field will also cause a gradual drift of mantle particles into the tail lobes toward the center of the tail (Figure 8). This drift may play an important role in the transfer of mantle plasma to the plasmasheet (Pilipp and Morfill, 1976; see also Section 4).

The boundary layer consists of a flow of magnetosheath-like plasma behind the magnetopause at low latitudes (e.g., Akasofu *et al.*, 1973b). This flow is expected to be mainly transverse to the local magnetic field, seat of the dynamo mechanism discussed on p. 42 (see Section 5 and Eastman *et al.*, 1976). Laboratory experiments (Podgorny, 1976) also reveal the formation of a layer of viscious interaction flow in the closed field line region of an artificial plasmatail.

4. Problem No. 3: Plasma Storage, Acceleration and Release Mechanisms in the Magnetospheric Tail

The plasmasheet (Figure 4) is a reservoir of warm plasma particles in the magnetospheric tail with an inner edge located at about 7–10 R_e in the geomagnetic equator and a pair of 'horns' extending along magnetic field lines down into the ionosphere. It stretches along the tail past the Moon orbit. The plasmasheet has been predicted theoretically (Parker, 1958; Piddington, 1960) and seems to be an intrinsic feature of the interaction of a plasma flow against a magnetized obstacle (Figure 2); characteristic signatures of a plasmasheet have also been observed in laboratory experiments (Podgorny, 1976). The plasmasheet sustains the current sheet which divides the tail into two lobes of nearly opposite magnetic fields (Figure 2). It is the seat of fundamental processes that control the dynamic response of the magnetosphere to certain changes in solar wind conditions.

Three facts make the theoretical and experimental study of the plasma sheet particularly difficult. One is that the actual configuration of the plasmasheet, in particular its thickness and inner edge position, depend significantly on the class and energy range of particles that are being considered. The second complicating factor is that the plasmasheet cannot be studied in isolation: its dynamic behavior is regulated by coupling mechanisms to the resistive ionosphere (Section 5) on one hand, and to the solar wind (Section 3) on the other. Third, a steady state of the plasmasheet of the terrestrial magnetosphere is never achieved in practice because of the particular time-scale of solar wind perturbations which trigger instabilities in the magnetospheric tail. These instabilities may be of a spatially limited scale so that different regions of the plasmasheet may be in different dynamic states at the same time.

Broadly speaking, the plasmasheet consists of charged particles whose residence time in the magnetospheric tail is controlled by their motion in the peculiar magnetic field geometry of stretched field lines. This peculiar geometry is caused by the drift-current of the particles themselves; hence the whole problem of the plasmasheet demands a self-consistent approach from the theoretical point of view (see reviews by Hill, 1974; Schindler, 1975; and Cowley, 1976). In particular, the boundary and self-consistency conditions to be satisfied by any steady-state plasmasheet theory must interrelate the particle injection mechanisms, the plasma and cross-tail current densities and the particle loss mechanisms.

Three mutually non-exclusive particle injection mechanisms have been postulated. One represents the entry of magnetosheath particles into the boundary layer

(p. 42) and magnetic drift from there through the plasmasheet. The other mechanism requires the existence throughout the magnetospheric tail of a large-scale electric field directed from dawn to dusk, responsible for the drift of mantle particles into the tail lobes toward the center of the tail (p. 45 and Figure 8), where they are drift-captured in the stretched magnetic field line region. Finally, the existence of the polar wind (e.g., Lemaire and Scherer, 1973) and the observations of helium and oxygen ions flowing upwards from the high-latitude ionosphere along field lines (e.g., Hoffman *et al.*, 1974) indicate that the ionosphere is a potential source of plasmasheet particles.

The total solar wind flux striking the magnetosphere cross-section is typically of the order of 10^{29} particles s^{-1} (Brandt, 1970). Allowing for the fact that the incident flow is deflected in the magnetosheath (see Figure 5c), the actual flux of solar wind particles impinging on the boundary may be smaller by perhaps two orders of magnitude. And, of course, only a certain fraction of these particles will actually penetrate into the magnetosphere. This leaves the estimated upper limit of total particle entry available for the plasmasheet between 10^{26}–10^{27} s^{-1}. On the other hand, the total escape rate of ions from the ionosphere has been estimated at 3×10^{25} s^{-1} (Hill, 1974). No quantitative estimate exists for possible direct entry rates through the flanks of the magnetopause into the plasmasheet. It is quite conceivable that all three abovementioned entry mechanisms are operative simultaneously, with a relative importance that depends on position along the tail and on solar wind parameters (the IMF).

The cross-tail current intensity is sustained by the plasmasheet particles. In absence of an electric field, individual particle motion in a stretched field line geometry depends on the energy of the particle and on its pitch angle (e.g., Fejer, 1965; Speiser, 1965; Bird and Beard, 1972). Particles with small enough energy so that their cyclotron radius in the minimum-B region (where $B \approx B_z$) is at all times much smaller than the minimum radius of curvature R_c of the field line (Figure 9a) will behave adiabatically, and curvature-drift in the current sheet region with velocity $V_c = (mv_\parallel^2/eR_cB_z)$ (Roederer, 1970) (the gradient-B drift is negligible in comparison). If the above condition is not met, or if V_c turns out to be of the order of, or greater than $v_\parallel$, the motion in the current sheet region is non-adiabatic. Under certain conditions, the particle can be temporarily trapped in the current sheet in a 'meandering' mode with the time-scales of 'bounce' and 'cyclotron' motion reversed (Figure 9b). The effect of a large-scale dawn-dusk electric field throughout the tail lobes is to cause an electric drift with velocity $\mathbf{V}_l = \mathbf{E}\times\mathbf{B}/B^2$ toward the current sheet region, and, if the particle is captured therein, an earthward drift with velocity $\mathbf{V}_e = \mathbf{E}\times\mathbf{B}_z/B_z^2$ (Figure 9c; Eastwood, 1972). If electric field drift entry from the two tail lobes were the *only* injection mechanism into the plasmasheet, the cross-tail linear current density $\lambda(A/m)$ would be directly related to the flux of particles drifting into the current (Alfvén, 1968). Indeed, if B is the field intensity in the tail lobe and n the number density of particles drifting toward the current sheet, one obtains the relation $B^2/\mu_0 \approx ne\Delta V$ (rationalized SI units), where ΔV is the electric

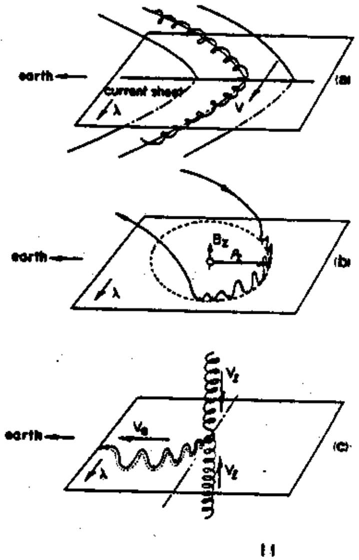

Fig. 9. Sketch of possible particle trajectories in the plasmasheet (see text).

potential difference between the dawn and dusk flanks of the tail (Figure 9c). Quite generally, since $e\Delta V$ is likely to be an order of magnitude larger than the average kinetic energy of a solar wind particle, the cross-tail electric field is bound to have considerable influence on the structure and the behavior of the plasmasheet (Cowley, 1976). A recent study of particle motion through a model cross-tail current sheet (Swift, 1977) has quantitatively shown that indeed, nonadiabatic encounters of mantle or lobe plasma particles with such a magnetic field structure (with an assumed electric field) are sufficient to create the characteristics of a plasmasheet population (see also Pudovkin and Tsyganenko, 1975).

On the other hand, since it is believed that (at least during quiet times) plasmasheet particles reside on closed field lines (absence of lunar shadowing, see further below), their behavior will be dynamically coupled to the portion of the ionosphere intercepted by these field lines. In particular, the electric fields in the plasmasheet and in the ionosphere will be interrelated through these field lines which are equipotentials in absence of anomalous resistivity (or on which the parallel electric field component is controlled by the field-aligned current if this resistivity is non-zero). Taking into account that ionspheric conductivity is strongly influenced by particle precipitation

(with or without anomalous resistivity), we have here a closed chain of cause-and-effect relationships (Figure 10) that is most difficult to describe quantitatively (e.g. Vasyliunas, 1970; Gurevich *et al.*, 1976). A self-consistent description of the plasmasheet must take these effects into account (Rostoker and Boström, 1976; see also Section 5).

There are two possible major particle loss mechanisms for the plasmasheet in a steady state, which most likely play a crucial role in determining its configuration during quiet times. One is direct particle loss through the magnetopause into the magnetosheath; the other is particle convection toward the Earth and precipitation into the ionosphere. The total loss rate associated with precipitation during quiet times has been estimated at 10^{25}–10^{26} particles s^{-1} (Hill, 1974), comfortably below the estimated maximum solar wind injection rate (p. 47) (but too high to have the plasmasheet accounted for entirely by a polar wind source). The earthward boundary of the plasmasheet probably corresponds to the region where pitch angle scattering into the ionosphere and convection into the magnetopause dominate over local particle replenishment.

So far we have focused our attention on a 'steady-state' plasmasheet. This represents, however, a highly hypothetical situation. Indeed, as mentioned above, a steady state is really never achieved. Changes in the interplanetary magnetic field cause changes in the topology of magnetic field connection across the magnetopause (Section 2) which in turn affects the particle transfer from magnetosheath to magnetosphere (Section 3). Under certain circumstances this is followed by a large-scale instability in the tail, the magnetospheric substorm (e.g., Akasofu, 1976a). Even a steady solar wind flow with persistent southward IMF appears associated with a sequence of these instabilities (see below).

Broadly speaking, the 'expansive phase' of a substorm represents the sudden transition of the tail plasma system toward a more stable state. This reconfiguration

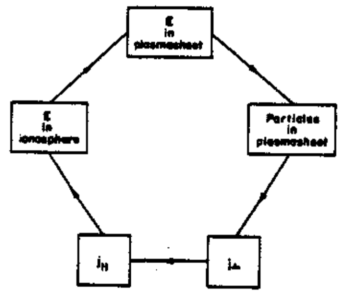

Fig. 10. Closed chain of cause-and-effect relationships regulating the electric field in the plasmasheet-ionosphere system.

occurs in the direction of higher to lower cross-tail current intensity, and from lower to high plasmasheet particle kinetic energy (ordered as well as random) (Hones, 1976). In other words, this transition consists of an implosive conversion of magnetic energy, accumulated prior to this implosion during a period called the 'growth phase' by some investigators, into particle energy. After the expansive phase, tail and plasmasheet undergo a slower 'recovery phase' toward a state more similar to one that existed during pre-substorm conditions. There are indications (e.g., the pole-ward expansion of auroral effects) that the instability starts somewhere in the near-earth end of the plasmasheet and propagates down the tail, and that this instability is often triggered by a southward turning of the IMF. There is no general consensus regarding the actual size of the plasmasheet region primarily involved in this instability and no general agreement on the detailed time-sequence of events in the associated reconfiguration process (see further below).

The plasmaphysical process of magnetic merging or reconnection (p. 32) has been invoked as a plausible cause of the field, plasma and energy reconfiguration that is believed to take place in the tail during the so-called expansive phase of a magnetospheric substorm (e.g., reviews by Russell and McPherron, 1973; Schindler, 1975). Spontaneous merging is an attractive candidate because it appears as a rather basic and universal process of magnetic energy dissipation in astrophysical plasma systems (Vasyliunas, 1975), yielding a number of qualitative predictions about plasmasheet and magnetotail behavior during substorm conditions (see below) that seem to match the observations, especially concerning the control by the north-south component of the IMF. An often quoted (but by no means universally accepted) sequence of events is the following (Figure 11): (i) A southward turning of the IMF increases the rate at which plasma flux tubes are transferred from the solar wind to

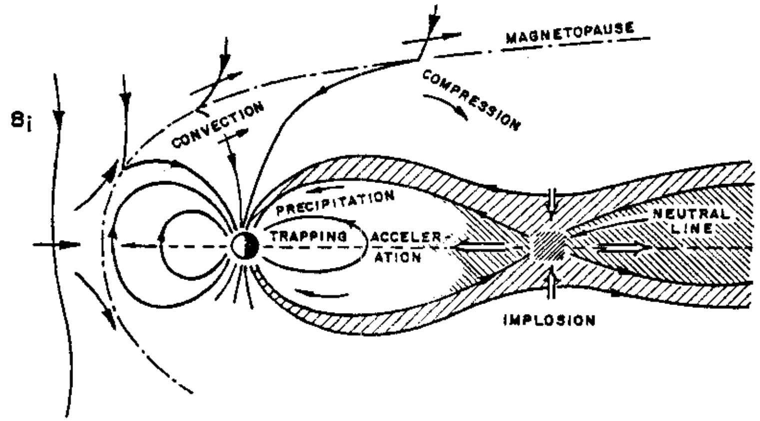

Fig. 11. Sketch of plasma flows in a substorm model based on a magnetic merging process occurring in the magnetospheric tail.

the tail (p. 30); (ii) As a result, the cross-tail current intensity increases, tail field lines are increasingly stretched, and the intensity of the mutually opposing fields in the tail lobes increases; (iii) If the southward-directed IMF persists, the thickness of the plasmasheet decreases, an X-type neutral line (or several of them) is formed in the cross-tail current sheet, and a merging process is eventually triggered along the neutral line leading to a plasma flow as shown in Figure 11; (iv) The plasma stream flowing toward the Earth is accelerated by the effect of magnetic drift in an enhanced dawn-dusk electric field, feeding ring current and particle precipitation, while the plasma portion flowing down the tail (Figure 11), is ejected into the solar wind; (v) As this process continues, the neutral line migrates down the tail until the magnetic field relaxes back to a less stretched, more dipole-like configuration.

Assuming that the sequence of events indeed does take place as described above, it is not at all clear whether the existing quantitative theories of merging (e.g., review by Vasyliunas, 1975) can be applied to this process. First, these tend to focus mainly on the processes that take place in the region of MHD breakdown and in the immediate neighborhood of the X-line without treating the macroscopic system with all its distant boundary conditions as a whole. Second, they do not take into account the effects of $\partial B/\partial t$-induced electric fields that must be prominent during the rapid magnetic field reconfiguration of a substorm (Nishida and Obayashi, 1972; Heikkila and Pellinen, 1977).

The first abovementioned restriction is mainly due to the extreme difficulty of devising a self-consistent quantitative theory of the macroscopic plasma system of the geomagnetic tail. However, it imposes serious limitations to the applicability of existing merging theories. For instance, just consider the question of the location of the neutral line. By definition, the neutral line is the locus of points where $\mathbf{B} = 0$. The magnetic field in the cross-tail current sheet (essentially directed along the z-axis in solar-magnetospheric coordinates) has several partly independent constituents: the internal geomagnetic field $\mathbf{B}_D$; the field of the magnetopause currents $\mathbf{B}_P$; the field $\mathbf{B}_I$ determined by the IMF interconnection topology (i.e., given by the distribution of $\mathbf{B}_\perp$ on the boundary (p. 31)); the field $\mathbf{B}_T$ determined by the cross-tail current sheet and magnetic-field-aligned currents in the plasmasheet; and the field $\mathbf{B}_L$ due to local current perturbations in the plasmasheet. A neutral line in the tail can thus appear because of 'distant' causes such as an intense overall cross-tail current intensity (so that $\mathbf{B} = 0$, mainly because $\mathbf{B}_D + \mathbf{B}_P + \mathbf{B}_T = 0$); a southward interplanetary field partially penetrating into the tail (so that $\mathbf{B}_D + \mathbf{B}_P + \mathbf{B}_I = 0$)*; or because of 'local' causes such as a strong current density gradient downstream from the neutral line (so that $\mathbf{B}_D + \mathbf{B}_P + \mathbf{B}_L = 0$). Occurrence, position and motion of neutral lines in the tail are thus controlled by local *as well as distant* current systems. None of them can be separately ignored in a quantitative study of the plasma system in question: the magnetospheric tail and its connection to the ionosphere must be considered as one integral system whose parts cannot be treated in isolation.

* The neutral point N_2 of Figure 3a is determined by IMF penetration.

Neglect of the induced electric field caused by a magnetic field reconfiguration, too, may lead to an unrealistic description of the plasmasheet behavior during substorm conditions. For instance, consider Figure 12 (Roederer, 1973). A southward-directed interplanetary field represents that configuration which is most efficient for plasma transfer to region II field lines in an open magnetosphere (Figure 2). We shall assume that a sudden increase of plasma transfer into the tail leads to a gradual increase in cross-tail current sheet linear density λ (as a result of gradual increase in particle number density), causing the observed increase of the magnetic

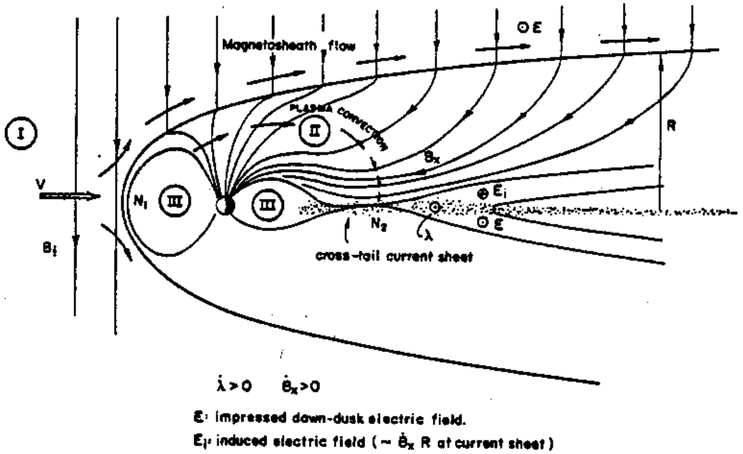

Fig. 12. Sketch of plasma convection in a model in which the cross-tail current density increases with time so as to prevent energy dissipation in the plasmasheet.

field intensity B_x in the tail lobes. An induced electric field E_i will appear, easily shown to be of the order of $\frac{1}{2}\mu_0\dot{\lambda}(R-|z|)=\dot{B}_x(R-|z|)$ (R: thickness of tail lobe, Figure 12; z: distance to current sheet), directed from dusk to dawn.* This induced electric field opposes the impressed solar-wind convection field **E**, with the result that the plasma drift velocity in the tail lobes $(\mathbf{E}+\mathbf{E}_i)\times\mathbf{B}_x/B_x^2$, directed into the current sheet, will decrease as the latter is approached (Figure 12). The plasma tubes will be seen to pile up and the field lines to gradually stretch out (plasmasheet thinning, see below). In other words, plasma will drift out of region II at a slower rate than it is drifting in through the dayside. In addition, the tail current increase will cause a shift of the neutral line N_2 toward the Earth (a purely field-geometric effect), and a decrease of the magnetic flux in the closed field region III on both dayside and

* For $\dot{B}_x=20\gamma/\text{hr}^{-1}$ (e.g., Russell *et al.*, 1971) and $R=25R_e$, $E_i=0.9\,\text{mV m}^{-1}$ in the cross-tail current sheet.

nightside (also a purely field-geometric effect). If the induced electric field happens to exactly neutralize the convection field, the flow of plasma into the neutral line N_2 would be exactly zero and there would be no energy dissipation or energy generation in the current sheet.

A sudden collapse of the cross-tail current density λ (e.g., by current flow diversion along field lines into the resistive ionosphere or by a sudden increase of local resistivity) would induce an electric field that now will be directed from dawn to dusk, i.e., in the same direction as the impressed convection field **E** (but much more intense), and the plasma flux tubes that previously were apposing onto the cross-tail current sheet would rush into the latter and break at the neutral line N_2, which, because of the decrease in λ, will be seen to move to the right in Figure 12, down the tail. *Everywhere* along the current sheet (not just at the neutral line) will we have $\mathbf{j}\cdot(\mathbf{E}+\mathbf{E}_i)>0$. The Poynting vector will be directed into the current sheet everywhere, and electromagnetic energy will be converted into particle energy all along the neutral sheet. Highly localized temporal changes in current density would produce particularly strong locally induced electric fields (Heikkila and Pellinen, 1977). This example shows that a merging process on a neutral line is not a necessary requirement to explain energy dissipation, field reconfiguration and particle acceleration during a magnetospheric substorm. The primary mechanism in the above example is the sudden collapse of cross-tail current with associated induced electric field effects. Of course, the neutral line may be instrumental in providing the region of enhanced resistivity that triggers the cross-tail current collapse.

To summarize our point in near-trivial fashion: whenever a current sheet collapses, elementary considerations (e.g., Lenz rule) show that the local (induced) electric field $\mathbf{E}_i$ will be such that $\mathbf{j}\cdot\mathbf{E}_i>0$ (trying to counteract the decrease of $|j|$). This necessarily implies that electromagnetic energy, tapped from the system's magnetic field energy reservoir, will flow into the collapsing current region, where it is being converted into mechanical energy. If the resistivity is strictly zero everywhere, the available mechanical energy will appear in the form of plasma bulk flow acceleration which, if there are strong magnetic gradients as in a 'near-neutral' sheet, can be very large indeed. The actual configuration and direction of the $\mathbf{E}\times\mathbf{B}/B^2$ flow will of course depend on the *total* fields ($\mathbf{B}_{\text{current}}+\mathbf{B}_{\text{distant sources}}$; $\mathbf{E}_i+\mathbf{E}_{\text{electrostatic}}$). If the local resistivity is finite, part of the released energy will be converted into thermal energy and field-aligned streaming. If the resistivity along magnetic field lines is finite, too, a field-aligned electrostatic-type electric field may build up and accelerate particles parallel to the magnetic field lines. Note that in the above picture there is no mention of neutral lines and field line merging or reconnection. The appearance of plasma acceleration and/or plasma jetting in the magnetotail can *not* be taken as an unambiguous test for merging – it could merely point to the occurrence of localized, short-term, perhaps turbulent time variations of the cross-tail current density. All this does not, of course, exclude the possibility that merging does take place as an additional plasmaphysical process in the plasmasheet. Finally, it should be noted that there is no *a priori* restriction on the intensity of an induced electric field, particles can be accelerated to high energies (whereas acceleration in an electrostatic field is always bounded by the maximum potential difference that appears in the system).

The study of plasma storage and release mechanisms in the magnetospheric tail, chosen here as 'task number three', has persistently remained a most fundamental problem since the very inception of magnetospheric physics. It also continues to feature most controversial 'schools of opinion', perhaps because, almost paradoxically, it surpasses every other subject of magnetospheric physics in terms of wealth of available experimental information. Indeed, it involves many magnetospheric effects such as geomagnetic variations, optical auroras and particle precipitation which are accessible to observation from the ground or from balloons and rockets. What makes this study so difficult is the need to tie all observed manifestations causally together, both in space and time. Yet time-sequences and spatial locations of occurrence strongly depend not only on *what* particular effect is being observed, but also on the specific *range* of energies, frequencies or other parameter values to which a given instrument is sensitive.

Both in the experimental and theoretical study of the plasma storage and release mechanisms in the tail, it is necessary first of all to clearly separate quasi-steady-state situations from those involving large-scale instabilities. The understanding of particle injection, storage and release mechanisms in the plasmasheet during quiet conditions is indeed of special importance. Concerning injection, observations at lunar distance in the tail have provided most valuable information. Evidence is accumulating that the lobes of the magnetospheric tail are filled with cool plasma of characteristics similar to those of the mantle and boundary layer, flowing antisunward along the magnetic field (e.g., Hardy *et al.*, 1976), and drifting toward the cross-tail current sheet (McCoy *et al.*, 1975). The ion temperature of the lobe plasma is of the order of 3 eV; number densities range between 0.1 and 3 cm^{-3}. The spatial distribution of this plasma throughout the tail cross-section is found to be correlated with the solar-magnetospheric y component of the IMF (Hardy *et al.*, 1976) with characteristics similar to the correlation between the dawn dusk distribution of the polar cap electric field and B_{iy} (*Heppner*, 1972). On the other hand, the observations of particle acceleration in the vicinity of the boundary in the low-latitude flanks of the magnetosphere (Frank *et al.*, 1976) point to the possibility of another, probably concurrent, continuous, and more direct injection mechanism into the plasmasheet. Finally, although the polar ionosphere cannot be ruled out as a particle source for the plasmasheet, the observed values of polar wind flux (p. 47) seem to be too low to account for a significant contribution. A similar conclusion is reached when the relative abundance of doubly charged helium among the precipitating ions is considered. However, it it clear that the O^+ ions observed in the distant tail (Frank *et al.*, 1977a) should mainly be of ionospheric origin, accelerated, thermalized and fed into the tail plasma by some as yet unidentified mechanism.

The quiet-time plasmasheet is considerably hotter (~0.5 keV ion temperature) than the inflowing lobe plasma, of a number density between 0·5–0·8 cm^{-3} (e.g., review by Hill, 1974). Electrons have average energies that are systematicalty 2–5

times lower than the proton energies. These facts indicate that capture in the plasmasheet after injection must be accompanied or preceded by substantial heating; the difference in ion and electron spectra suggests that this heating should be the result of a thermalization effect on an initially ordered accelerated particle flow (Frank, 1976). The considerable decrease in particle density from magnetosheath-lobe plasma to the plasmasheet (more specifically, the decrease in phase-space density) points to the operation of a highly selective or highly diffusive entry and acceleration mechanism (Hill, 1974). A physically most significant finding is the observation that the energy spectrum of plasmasheet particles in Mercury's 'mini-magnetosphere' (Ogilvie *et al.*, 1976) is nearly identical to that of the terrestrial plasmasheet particles. Taking into account the different temporal and spatial scale-sizes of both magnetospheres (and the fact that Mercury does not have an atmosphere), this spectral similarity must be considered as an important piece of information in the theories of plasmasheet generation and dynamics.

The absence of lunar shadowing effects on plasmasheet particles (Chase *et al.*, 1973) has been interpreted as an indication that the main particle source lies on the earthward side of the Moon and that the plasmasheet resides on closed field lines (class III, Figure 2), at least out to 60 R_e. At the lunar distance the plasmasheet has a structure similar to that at the Vela orbits (18 R_e), but the energy density is down by a factor of 5. This could be explained by assuming a persistent adiabatic flow of plasmasheet particles toward the Earth in a large-scale dawn-to-dusk electric field. Some observations, however, do not reveal any organized flow above detection threshold during quiet times (Stiles *et al.*, 1977). A most recent statistical study with different instrumentation (Frank *et al.*, 1977b) shows that proton bulk flows in the plasmasheet have the following characteristics: (i) flows are normally present but the grand total vector average is zero; (ii) flows are long-term events (of the order of hours or more); (iii) flow velocities can be sunward or antisunward with a comparable transverse (y) component; (iv) quiet-time average flow speeds increase from about 60 km s^{-1} at the earth-side flanks to 100 km s^{-1} 30R_e down the tail; (v) during disturbed times ($AE \geq 500$) the corresponding average speed values range from about 100 to 200 km s^{-1}; (vi) average proton flow speeds in the dusk side of the plasmasheet are about 30% higher than those measured in the dawn side.

At this time it is difficult to ascertain the extent to which injection, acceleration and thermalization are continual processes, or whether their contribution is significant only sporadically, during the development of large-scale instabilities in the tail. The fact that parts of the plasmasheet have been seen to heat up to 1–3 keV during a substorm and thereafter gradually cool down (even to 100 eV or less) certainly reveals that the substorm instability does play a very important role as a kinetic energy source for plasmasheet particles. The question at heart here is: if all substorm activity were to cease for good – into what regime would the plasmasheet settle?

The behavior of the plasmasheet during substorms has been a subject of intensive studies in recent years, with in situ satellite measurements correlated with ground-based observations (e.g., reviews by Russell and McPherron, 1973; Akasofu, 1976a). The difficulties of reaching an unambiguous interpretation of the results are overwhelming because of the complexity of the phenomena under consideration, their huge spatial extent, and their apparent refusal to follow standard patterns. Since neither ground-based observatory networks nor satellites cover space and time in a near-continuous fashion, it is extremely difficult to determine with a statistical study whether two types of correlated events are causally connected, or whether the occurrence of one simply caused the other, which took place *anyway*, to appear at the observational network used in the study (e.g., Feynman, 1976). For example, an important task is to determine whether the southward turning of the IMF is the primary cause of single substorm occurrence (e.g., McPherron *et al.*, 1973), or whether it merely contributes to enhance the detectability of the ground-effects of a substorm that is occurring anyway (e.g., Akasofu *et al.*, 1973a). Another factor that complicates statistical studies of the correlation between the IMF and substorm occurrence is the possibility that periods of unusually large southward component of the IMF can lead to a *sequence* of substorms (of decreasing intensity) that subsists even *after* the IMF has turned northward (Akasofu, 1976b).

The detailed analysis of isolated substorm events, though of key importance in an initial 'exploratory' phase of the study, has yet to yield the picture of a 'typical sequence of events' in the magnetotail on which most experimenters can agree. Maybe there is no such thing as a 'typical' sequence. For instance, while there are relatively undisputed indications that intense plasma cloud injections into the inner magnetosphere take place during or just after the expansive phase of a substorm (e.g., De Forest and McIlwain, 1971) and that a strong, transient, localized electric field in the near-earth tail must be involved (Roederer and Hones, 1974), observations of plasma flows, particle bursts and the magnetic field in the plasmasheet have yet to lead to a consistent picture. This is particularly true in regard to the scale size, location, and evolution of the initial instability region. Antisunward flows of plasma at $\sim 18\ R_e$ (e.g., Hones *et al.*, 1974) with southward-directed magnetic field in the tail (e.g., Nishida and Nagayama, 1975) have been interpreted as being evidence for the formation of an X-line in the near-earth plasmasheet (Figure 11) and subsequent down-tail migration. But this interpretation has recently been challenged (Lui *et al.*, 1976). On the other hand, there are observations of solar particle fluxes (Lin *et al.*, 1976) and of energetic electron bursts (Baker and Stone, 1976) whose anisotropy is characteristic of class I field lines in the magnetotail (Figure 2), while a detailed analysis of antisunward plasma flow during one particular substorm has led to the suggestion that a plasma structure with class IV field lines (Figure 2), termed 'plasmoid,' is formed earthward of the observing spacecraft and then ejected down-tail (Hones, 1976). Strong ($>1000\ \mathrm{km\,s^{-1}}$) streaming of plasma has been reported to occur in the magnetotail (Frank *et al.*, 1976) on certain occasions (which happened to correspond to substorms), directed earthward if the local **B** vector (normally parallel to the cross-tail current sheet) is tipped northward, and away from the earth if tipped southward. This in turn has been interpreted as evidence for a *localized* merging region (called 'fireball') situated near the observing spacecraft.

At higher particle energies, the question of the scale-size and evolution of the acceleration region is not decided either. High intensity 50–200 keV proton bursts (Keath *et al.*, 1976) have been observed at $\sim 35\ R_e$ predominantly in the dusk side of the plasmasheet (in correlation with intensifications of the westward auroral electrojet during substorms) directed tailward during the expansive phase and earthward during recovery. These observations again seem to point to an extended source and acceleration region that first appears in the near-earth region and then migrates down the tail. On the other hand, the analysis of simultaneous measurements of 200–500 keV proton anisotropies from two spacecraft with fine time resolution points to the existence of acceleration regions that are small (compared to the average proton gyroradius), mobile (sometimes with earthward motion), intrinsically time-varying (with a characteristic time scale of ~3 min) and probably multiple (Sarris *et al.*, 1976b). Quite generally, the acceleration of particles to hundreds of keV in a few seconds in substorm-related events indicates the action of a localized, non-thermal mechanism, probably related to field-aligned electric fields and/or to strong induction fields (p. 52); magnetic merging does not seem to be a likely candidate (Sarris *et al.*, 1976b). However, the formation of a neutral X-line may play an important role in providing an adequate field topology for (i) 'linear' non-adiabatic particle acceleration in an induced electric field parallel to that line; (ii) transfer into a second stage of adiabatic (betatron) acceleration with high magnetic moment (because of a low B-value at injection) (Heikkila and Pellinen, 1977).

An 'unbiased survey' of the recent literature reveals that the various investigators seem to agree only on the following points: (i) Substorms tend to appear after a persistent southward-turning of the IMF; (ii) There is a thinning of the plasmasheet during some early stage of the substorm development; (iii) There is plasma flowing and/or streaming toward the earth as a result of the expansive phase, with associated betatron and Fermi particle acceleration; (iv) Strong antisunward particle flows are frequently observed and there is sporadic, non-thermal particle acceleration to high energies; (v) During the substorm there is a transition of a markedly stretched to a more dipole-like magnetic field configuration in the tail.

In general, a hierarchy of questions emerges in connection with the magnetospheric substorm mechanism. (1) Is a neutral X-line formed in the near-earth tail? (2) If it is formed, when does this happen, and in what proportion is its formation controlled by distant currents or by local currents (p. 51)? (3) If a neutral line is formed, does a merging process take place? (4) If a merging process does take place, is it the main cause of all other substorm manifestations, or is it just a 'circumstantial' effect of *local* energy dissipation in the plasmasheet? (5) Is there more than one neutral line, merging, heating, or acceleration region? (6) Is the assumption of a neutral line necessary at all? (7) Is the electric field, responsible for particle acceleration during a substorm, of a field-aligned nature or of inductive origin due to a cross-tail current collapse? (8) If so, is this current collapse strongly localized, or does it occur over an extended region of the current sheet? – and here we are back at question (1), because the case of a strongly localized current collapse will indeed favor the creation of a neutral line (p. 52)!

5. Problem No. 4: Magnetic-Field-Aligned Currents and Magnetosphere-Ionosphere Interactions

In the previous chapters we have alluded several times to some physical mechanisms responsible for a causal connection between processes in the magnetosphere and the ionosphere. The study of magnetosphere-ionosphere interactions is of particular interest, for it comprises physical mechanisms that could be directly or indirectly responsible for possible magnetospheric effects on man's most immediate environment, the lower atmosphere. As looked upon from the point of view of an ionospheric or atmospheric physicist, or as a geophysicist dealing with time variations of the geomagnetic field on the surface of the earth, the subject of magnetosphere-ionosphere coupling deserves a separate, full-fledged review that would extend well beyond the scope of the present article. Hence, we shall deal only in generalities, and restrict the problem mainly to certain aspects related specifically to the influence of the ionosphere on the quiet-time quasi-steady state of magnetospheric plasma. Transient processes such as the appearance of electric fields parallel to the magnetic field, the ionosphere as a source of magnetospheric particles, and effects of the magnetosphere on the ionosphere will not be discussed explicitly.

From the plasma-physical point of view, the study of magnetosphere-ionosphere interactions presents a most interesting opportunity to examine the behavior of a large-scale system in which the resistivity varies from zero to some finite value along any given magnetic field line. Two domains thus arise (Figure 13a): a region (P) in which the MHD approximation (1) is valid; and a region (R) in which relation (1) has to be replaced by

$$\mathbf{E}+\mathbf{V}\times\mathbf{B}=\eta\mathbf{j} \qquad (2)$$

($\mathbf{V}$ is the bulk velocity of the resistive plasma, η the resistivity tensor). Note that in earlier chapters we have mentioned possible MHD breakdown regions in the outer magnetosphere and solar wind (e.g., pp. 26, 31), but that these were all expected to be 'two-dimensional' or 'one-dimensional' entities, i.e., boundary layers or neutral lines of transverse dimensions of the same order or smaller than a typical ion gyroradius (with the exclusion of transient regions of strong particle precipitation with parallel electric fields).

The dynamic behavior of the plasma in the MHD region P (Figure 13a) will be influenced or controlled by the resistive region R. Both regions 'communicate' with each other by means of field-aligned currents $\mathbf{j}_\parallel$, i.e., electric charge exchange. Strictly speaking, there is only one, unique, plasma bulk velocity configuration for which no such field-aligned currents flow between the two regions. It corresponds to the case in which $\mathbf{j}=0$ in the resistive medium R, i.e., a situation in which the bulk flow velocity $\mathbf{V}_\perp$ is magnetic-flux-preserving along the *entire* magnetic field line

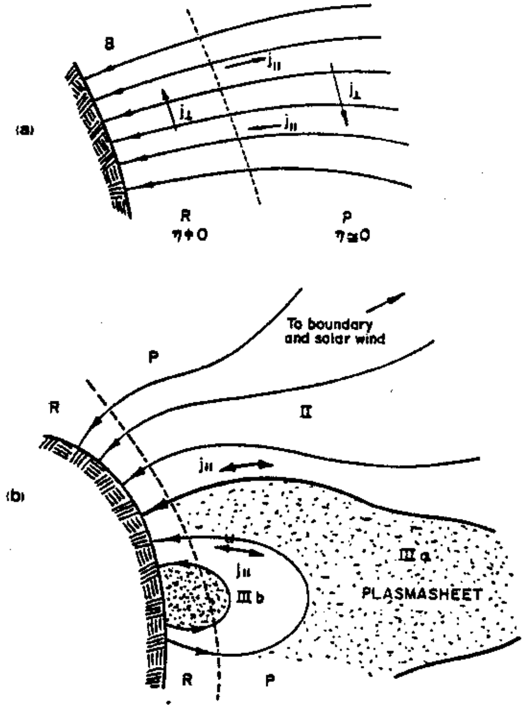

Fig. 13. An MHD region P coupled to a resistive region R (see text).

domain in both regions (note again that neither (1) nor (2) contains any information on the field-aligned streaming velocity $\mathbf{V}_\parallel$). In this configuration, the plasma in the MHD region 'co-moves' with the resistive gas (for instance, corotates rigidly if the central body is rotating (Vasyliunas, 1974)). The currents in the plasma region P must be fully closed inside that region – accumulation of free charges would not be allowed, with the only possible charge density being due to moving currents ($\varepsilon_0\mu_0\mathbf{V}\cdot\mathbf{j}$), and, eventually, local vorticity ($-(1/\varepsilon_0)\mathbf{B}\cdot\nabla\times\mathbf{V}$). This condition is possible only if no external forces are acting on the MHD plasma in region P. The resulting electric field (which also may have a solenoidal component if $(\partial B/\partial t)\neq 0$; for instance, when the rotating magnetic field is asymmetric) is precisely the one that causes the plasma to drift in co-motion with the resistive medium. The Lorentz force density $\mathbf{j}\times\mathbf{B}$ on the plasma is equal to $\rho\dot{\mathbf{V}}$ (ρ = mass density); this force system turns out to be non-dissipative.

Any flow configuration different from co-motion will entice $\mathbf{j}\neq 0$ somewhere in the resistive region. Since in general $\nabla\cdot\mathbf{j}_\perp\neq 0$ in that region ($\mathbf{j}_\perp$ = current density perpendicular to **B**), there will be parallel currents $\mathbf{j}_\parallel$ linking both domains (called 'driving currents' (Vasyliunas, 1974).) In the MHD region P, the current $\mathbf{j}_\parallel$ will necessarily be closed by perpendicular currents $\mathbf{j}_\perp$; the corresponding Lorentz force density $\mathbf{j}_\perp \times \mathbf{B}$ now plays the role of a viscous-type force on the plasma, trying to force the latter into co-motion. In the resistive region R the plasma contained in one given magnetic flux tube at one instant of time will not be found in a common flux tube at a different time. There is general energy dissipation, with kinetic energy of the plasma and/or work done by external mechanical forces acting on the plasma being converted into Joule heating of the resistive medium. (Note that this particular process is of importance in astrophysics (e.g., slowdown of pulsar rotation), laboratory plasma physics (e.g., a certain class of dissipative effects in mirror machines), and atmospheric physics (e.g., upper atmosphere heating).) As a result of all this, a plasma in the MHD region free of external forces that initially is not comoving with the resistive gas will end up doing so. On the other hand, consider a plasma disconnected from a resistive region, under the action of external forces of density **f**. Under such conditions, the plasma will be polarized (divergence of the force-drift current (e.g., Longmire, 1963)) in such a way as to generate an electric field that imparts a drift **V** whose acceleration turns out to be exactly $\dot{\mathbf{V}} = \mathbf{f}/\rho$ (i.e., the plasma will follow the dictates of the external forces). If this plasma is now coupled to a resistive region, the polarization charges will be drained into (or draw neutralizing charges from) the resistive medium in the form of field-aligned currents $\mathbf{j}_\parallel$: the polarization of the plasma will be altered, and so will the electric field configuration and associated plasma drift (bulk motion). Again, the end effect of the coupling is that of the appearance of viscous-type stresses on the plasma.

In a stationary state, the field-aligned current density $\mathbf{j}_\parallel$ is related to the transverse density $\mathbf{j}_\perp$ by $\nabla \cdot \mathbf{j}_\parallel = -\nabla \cdot \mathbf{j}_\perp$ (i.e., $-\nabla \cdot \mathbf{j}_\perp$ represents the 'source' of field-aligned currents). Points where $\nabla \cdot \mathbf{j}_\perp \neq 0$ are expected to lie in regions with particle density gradients such as plasma boundaries – thus the field-aligned currents $\mathbf{j}_\parallel$ connecting regions R and P of Figure 13a will preferentially flow along the field lines that project inhomogeneities and plasma boundaries arising in P onto the domain of R. Figure 13b shows schematically the boundary situation for an 'open' magnetosphere-ionosphere system. Region II is that of interconnected field lines intercepting the ionosphere in the polar cap (see also Figure 2). Region III is that of closed field lines which in Figure 13b has been further divided into two subregions: *IIIa* corresponds to field lines carrying the plasmasheet; *IIIb* to the plasmasphere and trough (Figure 4). From the above considerations one should expect the field-aligned magnetosphere-ionosphere currents, also called *Birkeland* currents, to flow along the field lines defining the various plasma boundary structures (e.g., Boström, 1974).

In region II (Figure 13b) the plasma flow and associated electric field are *impressed* by the processes responsible for the solar wind flow at the 'other end' (the base of the corona, p. 26); the electric field is mapped into the ionospheric domain along the interconnected field lines (p. 28), thus driving an antisunward plasma flow over the polar caps. A field-aligned current system must be expected on the boundary of

region II, with at least part of the closing currents $\mathbf{j}_\perp$ in the MHD region flowing in the magnetosheath or solar wind plasma (the tail lobe portion of region II field lines most probably could not sustain such currents). The direction of these closing currents will be such as to cause a breaking force $\mathbf{j}_\perp \times \mathbf{B}$ on the solar wind flow (e.g., Stern, 1977).* This necessarily will lead to a $\mathbf{j}_\parallel$ directed *into* the ionosphere at the dawn (post-midnight) side, and *out* of it at dusk (pre-midnight), as sketched in Figure 14a.

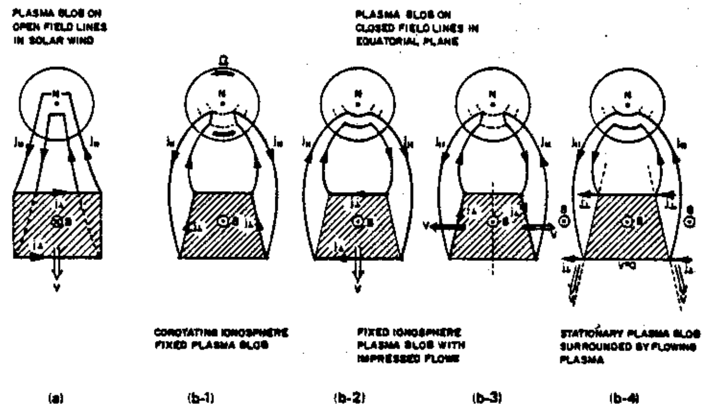

Fig. 14. Hypothetical cases of an MHD plasma region in the solar wind (a) or the plasmasheet (b) coupled to the earth's resistive ionosphere. V: impressed plasma flow; $\mathbf{j}_\parallel$: field aligned current; $j_\perp$: closing current in plasma (see text).

In an open magnetosphere the general electric field configuration over the polar cap (region II-R in Figure 13b) should thus be expected to be driven by a dynamo in the solar wind and modulated by the interconnection field topology (Section 2). In region III, on the other hand, the electric field should be driven by dynamos in the resistive ionosphere (forcing the magnetospheric plasma to co-move), plus possible MHD dynamos in the plasmasheet (controlled by external stresses). We identify two main large-scale ionospheric dynamos: (1) closure in region III-R of the flow impressed onto the polar region II-R or, equivalently, closure of electric equipotentials in the closed field line region III (Yasuhara and Akasofu, 1977); (2) viscous forces acting on the ionospheric plasma as a result of collisions with the neutral gas. In (2) we in turn distinguish two main contributions: (i) corotation of the neutral

* In a *closed* magnetosphere there would be no region II in Figure 13b. It would have to be replaced by a region of (closed) field lines threading the boundary layer where a viscous interaction with magnetosheath flow takes place (see p. 42).

atmosphere, and (ii) the global S_q flow system associated with the diurnal variation of solar-produced ionization (Matsushita, 1968). The plasmasheet dynamo would somehow be related to the injection mechanism and external stresses. Figure 14b shows four hypothetical cases. The first represents that of a 'plasma blob' (plasmasheet!) that is stationary with respect to the Earth-Sun system, and a rotating ionosphere. Field-aligned and closure currents are such as to provide a $\mathbf{j}_\perp \times \mathbf{B}$ force system that tries to compel the plasma into co-motion. The second case corresponds to a stationary ionosphere with a plasma blob that has an impressed tailward flow. In the third case, the impressed plasma motion is directed away from the tail center toward the flanks. In the second and third cases, the $\mathbf{j}_\perp \times \mathbf{B}$ forces are again such as to compel the plasma into co-motion (i.e., oppose the impressed flow **V**). The fourth case represents a stationary plasma blob surrounded by 'boundary layer'-type plasma flowing on closed field lines (p. 42).

In the real case of the magnetosphere, the actual configuration of the field-aligned current system will strongly depend on the topology of the magnetic field, e.g., the form of the boundary between open and closed field lines and its projection onto the ionosphere; magnetopause interconnection topology; and antisunward bending of magnetic field lines. This bending is especially important in case b-4 of Figure 14, where the field-aligned 'return' currents along the magnetospheric boundary field lines are not shown at all, for their topology would depend entirely on the field model assumed (e.g., Eastman *et al.*, 1976). It is important to note that the real field-aligned current system might well be a superposition of two or more of the elementary cases shown in Figure 14. Note, for instance, how the solar wind dynamo of Figure 14a reinforces the poleward $\mathbf{j}_\parallel$ currents of the case of Figure 14b-3, and how the full *dusk side* current system of the latter is reinforced (and the dawn side system attenuated) by the 'non-corotation' case (Figure 14b-1).

The above-mentioned ionospheric dynamo mechanisms (1) and (2) play a fundamental role in shaping the large-scale electric field in the closed field line region III (Figures 2 and 13b). Figure 15 is a sketch (not in scale) of the 'first approximation' quiet-time electric field configuration in the tailward portion of the magnetosphere. Marked on the equatorial surface are electric equipotentials, that is, electric drift lines of plasma particles (e.g., Brice, 1967; Chen, 1970; Volland, 1973). The detailed structure of the theoretically predicted electric field will of course depend strongly on how far the self-consistency picture shown in Figure 10 is carried through (e.g., Gurevich *et al.*, 1976), on the assumptions made on ionospheric conductivity (e.g., Yasuhara and Akasofu, 1977) and on the penetrability of the convection electric field into the corotation region (e.g., see reviews by Wolf, 1975; and Stern, 1977). The electric field configuration predicted for the dayside magnetosphere depends very critically on the assumptions made regarding the electric field on or near the magnetopause. A question of particular theoretical importance is whether or not part of the dayside magnetopause current system is diverted into the ionosphere via field-aligned currents. This has a strong bearing on the stability of the dayside boundary (p. 41).

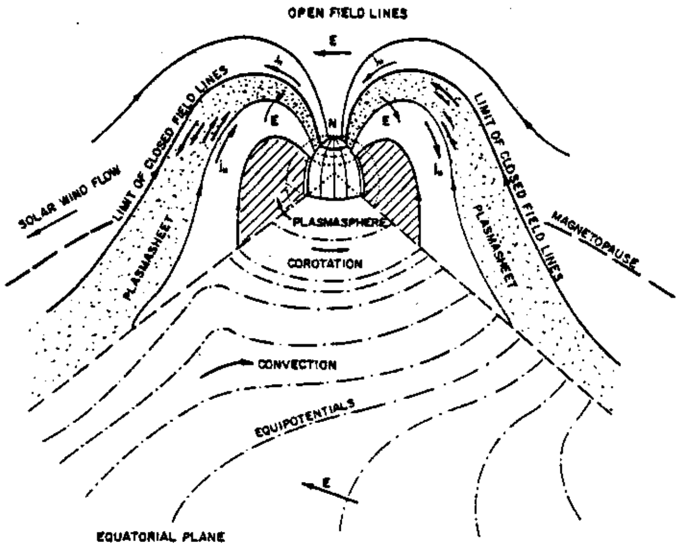

Fig. 15. Sketch (not in scale) of the quiet-time electric field configuration in the tailward portion of the magnetosphere. Marked on the equatorial surface are electric equipotentials (or plasma drift lines).

Although not an explicit subject of this article (p. 58), a few words on magnetic-field-aligned electric fields are in order (e.g., reviews by Stern, 1976; Evans, 1976). Quite generally, during transient conditions such as the development of turbulence in the MHD region *P* (Figure 13a) or microturbulence in the ionosphere (region *R*), a transition region between *P* and *R* may appear in which transient plasma processes establish a 'second order' coupling between the two regions, in addition to the 'first order' coupling given by $\mathbf{j}_\parallel$. One manifestation of this second order coupling is the buildup of a parallel electric field. Several classes of mechanisms for this transient phenomenon have been envisaged: (1) a temporary difference between the distribution functions of trapped electrons and protons (e.g., Block and Fälthammar, 1976); (2) turbulence (anomalous resistivity) caused by plasma instabilities in regions of strong field-aligned currents (e.g., Papadopoulos, 1977); and (3) current-driven electrostatic shocks (Swift, 1975).

It seems almost preposterous to relegate the study of magnetosphere-ionosphere interactions to 'task number four' of magnetospheric plasma physics. As was pointed out earlier, the subject is so multifaceted that it should be given a ranking all its own. Indeed, it comprises the study of field-aligned currents; the large-scale electric field in the closed field region; transient magnetic-field-aligned electric fields, associated ionospheric particle acceleration and auroral phenomena; cusp phenomena; the polar wind; formation of the plasmasphere; wave-particle interactions; ionospheric heating; propagation of polar disturbances to lower latitudes; etc. We shall deal below mainly with the first item, field-aligned currents, as perhaps the most basic manifestation of steady-state magnetosphere-ionosphere interaction.

Low altitude satellite measurements of the magnetic field have revealed a pattern of field-aligned currents (e.g., Zmuda and Armstrong, 1974; Iijima and Potemra, 1976) that has the following characteristics. (1) A poleward zone of field-aligned currents encircling the polar cap; 2–4° wide in latitude; with currents $j_{\parallel}$ flowing into the ionosphere in the morning side (maximum current density between 0700–0800 magnetic LT) and out of the ionosphere in the afternoon side (maximum at 1500–1600 LT); positively correlated with magnetic activity (K_p), but persisting even during very low activity. (2) An equatorward zone adjacent to zone (1), of systematically lower current density except in the night sector (2100–0300 LT); flowing away from the ionosphere in the morning sector (maximum current density between 0100–0300 LT) and into the ionosphere in the afternoon sector (maximum at 2100–2300 LT); correlated with K_p and the polar electrojets. See Figure 15 for the direction of this field-aligned current system in the tailward side of the magnetosphere. Note that it corresponds to the directions shown in Figure 14b-3. A field-aligned current system has important effects on the surface magnetic field, which thus can be used as a quantitative diagnostic tool (e.g., Fukushima, 1976).

The poleward zone (1) appears to be a permanent feature of the field-aligned current system. Measurements at greater distances from Earth (Sugiura, 1975) and comparisons with the trapping boundary (Sugiura and Potemra, 1976) indicate that this system flows near the poleward (lobeward) boundary of the plasmasheet (see Figures 13 and 15). The permanent component of this system might be driven either by a solar wind dynamo in the case of an open magnetosphere (Figure 14a) or by an antisunward-flowing boundary plasma in a closed magnetosphere (Figure 14b-4; see also Eastman *et al.*, 1976). The K_p-modulated component of system (1) is probably driven by a dynamo in the plasmasheet (e.g., the case of Figure 14b-3). In the ionosphere, it is possible that the closure currents $j_{\perp}$ merge poleward into the polar cap Sq^p system (e.g., Iijima, 1973; Yasuhara and Akasofu, 1977), and equatorwards into the zone (2) system.

The equatorward zone (2) of field-aligned currents seems to be intrinsically associated with the plasmasheet, especially its earthward boundary (Sugiura, 1975), and must be driven by a dynamo therein. Two different models have been proposed for the closure currents in the plasmasheet. One assumes $j_{\perp}$ to flow perpendicularly to the tail lobe-plasmasheet boundary (Rostoker and Boström, 1976) (the $\mathbf{j} \times \mathbf{B}$ force system thus being directed toward the midnight meridian of the tail from both premidnight and postmidnight sides). The other (Sugiura, 1975) assumes that zone (2) currents close through the cross-tail current sheet ($\mathbf{j} \times \mathbf{B}$ force system directed toward the Earth in the current sheet). Obviously both models would require quite different dynamo mechanisms (outflow of plasma from the center of the plasmasheet towards its flanks in the first model, (rather unlikely) tailward flow of plasma in the second one; see Figure 14b-2 and -3, respectively)). In the ionosphere, the equatorward zone (2) current system closes with the zone (1) system; indeed, the correlation with the polar electrojets strongly indicates that the latter represent the Hall currents associated with the poleward/equatorward closure currents of system (2) in the morning/afternoon sector.

The principal problem with field-aligned currents is the driving mechanism (Stern, 1977). How much is due to solar wind flow, how much to convective motions in the tail? Are parallel electric fields involved, are they a consequence of magnetic-field-aligned current intensification, or the cause thereof? What is the configuration of the closure currents in the solar wind/magnetosheath/tail lobes, in the plasmasheet, and in the ionosphere?

6. Prospects for Solution

In the previous sections we have analyzed four fundamental problems of magnetospheric plasma physics. Is there a chance that they will be solved in the near future? During the International Magnetospheric Study 1976–79, (e.g., *International Magnetospheric Study: Guidlines for United States Participation*, Natl. Acad. of Sci., Washington, D.C., 1973; summary by Roederer, 1976, *International Magnetospheric Study: Progress Report*, this issue, p. 3), the International Sun-Earth Explorer mission (ISEE) will carry out detailed plasma and field measurements conducted simultaneously at nearby points by means of a 'mother-daughter' pair of spacecraft to be launched in October 1977. Another spacecraft of this mission, to be launched in 1978, will be positioned near a Lagrangian point upstream in the solar wind to monitor the plasma input parameters. Observations of the state of the inner magnetosphere involve another IMS-dedicated spacecraft, the geosynchronous satellite GEOS, launched in April 1977. Intensive ground-based, balloon and rocket observations, coordinated over large regions of the globe, especially at high geomagnetic latitudes, many of them coordinated with GEOS, provide additional input on the global state of the magnetosphere, on magnetospheric perturbations and magnetosphere-ionosphere interactions.

Of the four major problems listed in this article, number 3 on plasma storage and release mechanisms and number 4 on field-aligned currents and magnetosphere-ionosphere interactions have the best chances of being solved to a significant extent during the IMS and post-IMS years. The IMS-dedicated satellite missions GEOS and ISEE, the post-IMS Dynamic Explorer program, the IMS chains of magnetometers and auroral cameras, IMS rocket and balloon campaigns, and continued data acquisition from operational satellites already in orbit will provide key information on the structure and the dynamics of the near-earth portion of the plasmasheet and field-aligned current effects at high latitudes and low altitudes.

There are, however, some conditions attached to the tapping of this extraordinary data base if real progress is to be made. (1) The analysis of *simultaneous multiple spacecraft observations, coordinated with ground-based, balloon and rocket measurements is necessary* to make the required distinction between spatial and temporal effects. (2) A deliberate effort must be made to spell out and discuss *a limited number of basic questions* whose answers can realistically be expected to be obtained with existing and planned programs. (3) Only a deliberately coordinated, collective effort of data acquisition *and interpretation* will make it more likely that some of the difficulties involved can be resolved. (4) Only a deliberately organized team effort by experimentalists *and theoreticians* can lead to credible, quantitative answers to the many questions posed.

More specifically, when it comes to substorm studies (Section 4), it is of particular importance that experimentalists and theoreticians give up subjective biases and join in an effort to seek the truth rather than the confirmation of pet ideas. Both experimentalists and theoreticians (including the author of this article) should eradicate from their brains the 'classical' mental image of a due-southward interplanetary field 'merging' with the terrestrial field (Dungey, 1961), give up overintuitive, overqualitative mental exercises with moving field lines, and start building a mental representation of the magnetospheric plasma system in which the relevant physical magnitudes are macroscopic distributions of electric charges and currents, bound together by the electromagnetic field. Both experimentalists and theoreticians should give up the habit of devising elaborate but only qualitative models based on the analysis of one single event or on the analysis of several events using data from only one spacecraft. In general, the event-oriented mode of data analysis and paper publication should be transformed into more systematic, synoptic and statistically oriented studies. Such a mode does not allow frequent publications; it is therefore urged that sponsoring agencies turn away from their entrenched 'publish-or-perish' policy and allow for a transition from short grant periods to at least 3-year funding.

Other procedures that need to be reformed are the following. Too many scientific papers are published prematurely and hence go unread by a large percentage of scientists. Too many data taken by one experimenter are misinterpreted by another, too many data are stored in World Data Centers without ever having been used by the original experimenters, and too many data are deposited there without enough specifications to be deciphered by other users. Finally, individual scientists, institutions and funding agencies are beginning to be skeptical of the present structure of international scientific meetings and information exchange on research results. There are too many meetings on broad, vaguely defined subjects, and too many symposia prematurely arranged on the discussion of individual events.

Tasks 1 and 2, and certain aspects of problem No. 3 require observations in the high-latitude, high-altitude magnetosphere. *Satellites and magnetospheric multi-probes in highly eccentric, high-inclination orbits are the only means to gather the necessary detailed information in the critical regions*; hence, the IMS will not lead to all the answers on these topics. However, this program can make substantial contributions to some aspects of tasks 1 and 2, involving the study of the low-latitude region of the boundary and underlying layers with the ISEE mother-daughter spacecraft, and of the low-altitude cleft using existing high-inclination satellites, an expanded sounding rocket program and appropriate ground-based, balloon and

aircraft observations. Important questions *can* be answered by such methods. They pertain to the mantle and boundary layer near the equatorial plane and to possible local entry processes which might not be operational at higher latitudes, i.e., to the possible existence of a sequence magnetosheath → boundary layer → plasmasheet. On the dayside, a systematic study of the low-latitude magnetopause structure will help clarify many questions related to its thickness, stability, and possible effects of the filamentary structure of the solar wind, and will permit a further search for a possible merging process on the magnetospheric boundary. A systematic study of the low-altitude cleft, in particular of convection patterns, impulsive injections, field-aligned currents and wave-particle interactions, may shed light on the complicated dynamical processes that are believed to occur higher up in the 'throat' and in the entry layer.

Quantitative theoretical research must be expanded, starting from 'first principles', trying to first quantitatively understand basic, elementary plasma paradigms (such as a Vlasov theory of the boundaries shown in Figure 7 and the dynamo mechanisms of Figure 14), and only after this is accomplished tying them together to build a quantitative model of the global magnetospheric system in a self-consistent way.

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