Ann. Geophysicae 10, 103–115 (1992) © EGS – Springer-Verlag 1992

Annales Geophysicae

Excitation and decay of solar wind-driven flows in the magnetosphere-ionosphere system *

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Received June 19, 1991; revised November 8, 1991; accepted November 29, 1991

Abstract. Basic concepts of the form of high-latitude ionospheric flows and their excitation and decay are discussed in the light of recent high time-resolution measurements made by ground-based radars. It is first pointed out that it is in principle impossible to adequately parameterize these flows by any single quantity derived from concurrent interplanetary conditions. Rather, even at its simplest, the flow must be considered to consist of two basic time-dependent components. The first is the flow driven by magnetopause coupling processes alone, principally by dayside reconnection. These flows may indeed be reasonably parameterized in terms of concurrent near-Earth interplanetary conditions, principally by the interplanetary magnetic field (IMF) vector. The second is the flow driven by tail reconnection alone. As a first approximation these flows may also be parameterized in terms of interplanetary conditions, principally the north-south component of the IMF, but with a delay in the flow response of around 30–60 min relative to the IMF. A delay in the tail response of this order must be present due to the finite speed of information propagation in the system, and we show how "growth" and "decay" of the field and flow configuration then follow as natural consequences. To discuss the excitation and decay of the two reconnection-driven components of the flow we introduce that concept of a flow-free equilibrium configuration for a magnetosphere which contains a given (arbitrary) amount of open flux. Reconnection events act either to create or destroy open flux, thus causing departures of the system from the equilibrium configuration. Flow is then excited which moves the system back towards equilibrium with the changed amount of open flux. We estimate that the overall time scale associated with the excitation and decay of the flow is about 15 min. The response of the system to both impulsive (flux transfer event) and continuous reconnection is discussed in these terms.

Introduction

The internal convection of plasma and magnetic flux which is driven by the surrounding flow of the solar wind is the single most important factor governing the structure and dynamics of the Earth's magnetosphere-ionosphere system (Cowley, 1980; Moore *et al.*, 1989). As a consequence, considerable efforts have been expended over the past 25 years to elucidate the nature of these flows and their dependence on the properties of the interplanetary medium (Cowley, 1983; Reiff and Luhmann, 1986). It has become evident, however, that a distinct sharpening of view has recently taken place on these topics, resulting primarily from high time-resolution studies of ionospheric flows which have been obtained from ground-based radar systems (Rishbeth *et al.*, 1985; Willis *et al.*, 1986; Etemadi *et al.*, 1988; Todd *et al.*, 1988; Lockwood and Cowley, 1998; Richmond *et al.*, 1988; Lester *et al.*, 1990; Knipp *et al.*, 1991). The purpose of this paper is to present a concise discussion of the conceptual picture which has emerged. A more detailed discussion of some aspects of this picture, together with summaries of the flow observations on which it has been based, may be found, in for example, papers by in Lockwood and Freeman (1989), and Lockwood *et al.* (1990b).

IMF dependence of ionospheric flows

Studies of ionospheric flows and their relation to interplanetary conditions began about 25 years ago, using electric field, plasma drift and magnetic perturbation observations from low-altitude spacecraft (the latter perturbations being associated with the related Pedersen current system). Magnetic observations from the ground (associated with the related Hall current system) were also

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* Paper presented at the workshop ST-17 on "Radar imaging of magnetospheric processes", EGS General Assembly, Wiesbaden 22–26 April 1991

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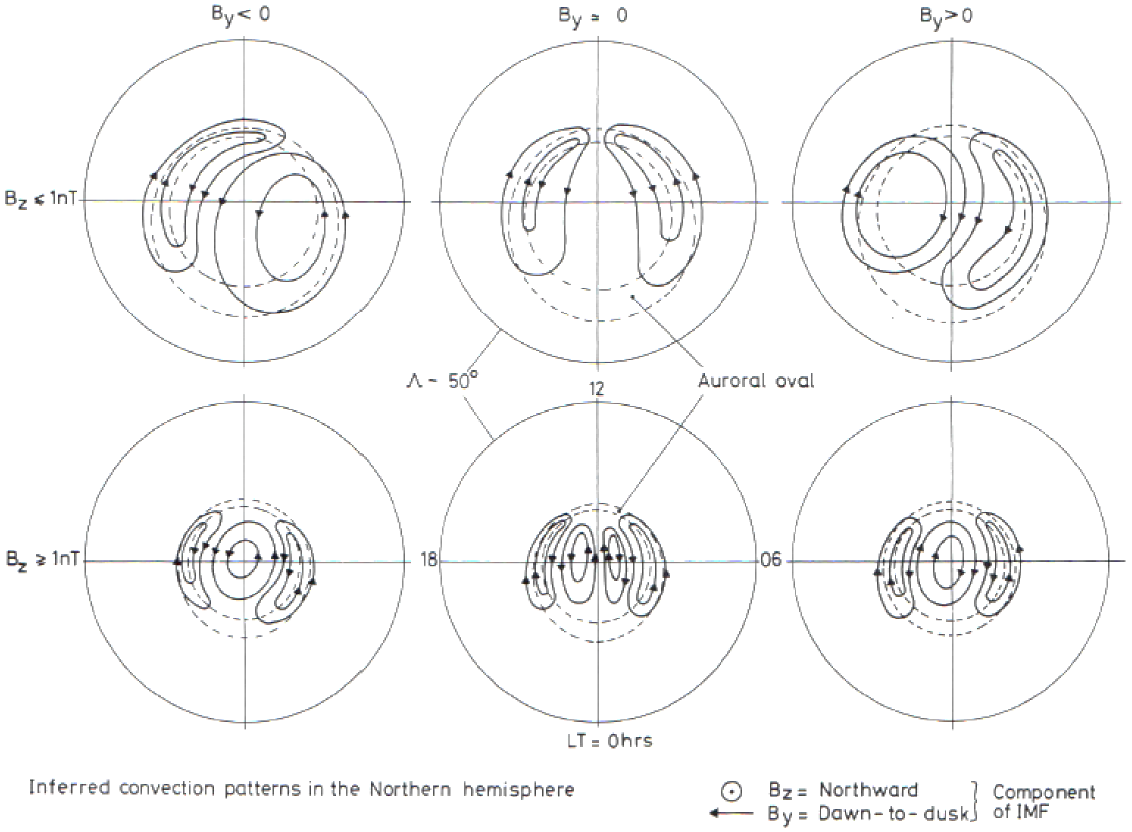

Fig. 1. Sketch showing the form of the high-latitude ionospheric flows in the Northern hemisphere for differing orientations of the interplanetary magnetic field. (After Lockwood, 1991 b)

used. These studies rapidly demonstrated the existence of three important effects, illustrated here in Fig. 1:

(a) For much of the time the flows at high-latitudes are of two-cell form, with anti-sunward flow over the polar cap and return sunward flow at lower latitudes in the auroral zones, as expected for solar wind-driven convection. However, both the spatial extent of the flow system and the magnitude of the flows are variable and are related to the North-South component (B_z) of the IMF. The flow system is larger and stronger when the field is southward (B_z negative) than when it is northward (Fairfield and Cahill, 1966; Nishida, 1968 a, b; Arnoldy, 1971; Heppner, 1972, 1973; Reiff *et al.*, 1981; Holt *et al.*, 1987; Lu *et al.*, 1989; Hairston and Heelis, 1990). The expansion for increasingly negative B_z is also reflected in the location of the aurorae (Vorobjev *et al.*, 1976; Horwitz and Akasofu, 1977; Holzworth and Meng, 1975, 1984).

(b) The twin-cell flow exhibits a number of dawn-dusk asymmetries, oppositely-directed in the Northern and Southern hemispheres, whose sense depends on the East-West component (B_y) of the IMF. These asymmetries involve the local time of the dayside cusp, the sense of the East-West flow in the cusp, gradients in the antisolar flow across the polar cap and dawn-dusk shifts of the "centre" of the polar cap, together with related magnetospheric effects (Mansurov 1969; Svalgaard, 1973; Heppner, 1972, 1973; McDiarmid *et al.*, 1978; Iijima *et al.*, 1978; Holzworth and Meng, 1984; Heppner and Maynard, 1987; Lu *et al.*, 1989; Newell *et al.*, 1989).

(c) Occasionally, however, sunward-directed flows are observed in the central polar cap which are indicative of multi-cell convection with (usually) three dominant cells. The sense of rotation in the central cell depends on B_y, having the same zonal sense as in case (b) above. Flows of this nature are typically observed when the IMF has a "significant" positive *z* component (B_z above about 2 *nT*) and may have a substantial magnitude while being confined to very high latitudes (Heppner, 1972, 1973; Maezawa, 1976; Burke *et al.*, 1979; Saflekos and Potemra, 1980; Zanetti *et al.*, 1984; Potemra *et al.*, 1984).

The basic theoretical explanation for all these effects has long been understood in terms of Dungey's (1961) "open" or "reconnection" model of the magnetosphere. First, the modulation of the flow by IMF B_z, and the amount of open flux which the system contains, is a basic prediction of the model, resulting from the expected dependence of the efficiency of dayside reconnection on the direction of the IMF. The latter dependence has also been demonstrated directly by in situ observations at the magnetopause (Paschmann *et al.*, 1979, 1986; Sonnerup *et al.*, 1981; Rijnbeek *et al.*, 1984; Berchem and Russell, 1984). Second, the "Svalgaard-Mansurov" and related effects are simply understood as resulting from the east-west tension exerted on newly opened dayside flux tubes in the presence of IMF B_y, leading to asymmetrical addition of open flux tubes to the tail lobes (Jorgensen *et al.*, 1972; Atkinson, 1972; Cowley, 1981; Saunders, 1989; Cowley *et al.*, 1991). Third, the flow effects observed within the central flow cell(s) when IMF B_z is positive are believed to result from reconnection between the IMF and pre-existing open flux in the tail lobe (Dungey, 1963; Russell, 1972; Crooker, 1979; Reiff and Burch, 1985). In the most probable case in which a given IMF field line becomes connected to one lobe only, the amount of open flux is not changed by this process but is instead "stirred" into circulatory motion by the transfer of open flux from one side of the tail lobe to the other, depending on the sense of IMF B_y. The additional flow cells at lower latitudes in this case are then ascribed to first order non-reconnection "viscous" coupling processes acting at the magnetopause boundary.

Thus from the earliest days, observations showed that the flows in the magnetosphere-ionosphere system are crucially dependent on the direction of the IMF. (In this paper we shall not consider the additional modifying effects which are due, for example, to non-uniform ionospheric conductivity). This realization led to a large number of studies, some of wich have been cited above, in which the IMF dependence of various aspects of the flow system were examined in detail (see also, for example, Friis-Christensen and Wilhjelm, 1975; Heelis, 1984; Rodger *et al.*, 1984; and the review by Shunk, 1988). In Fig. 2 we show an example of spacecraft measurements of the voltage across the central polar cap which is associated with the twin-cell flow, plotted versus the East-West component of the interplanetary electric field, VB_z, where V is the speed of the solar wind (compiled by Cowley, 1984, from the work of Reiff *et al.*, 1981; Doyle and Burke, 1983; and Wygant *et al.*, 1983). It can be seen that there is a very clear trend towards large voltages for negative VB_z and smaller voltages for positive VB_z, in line with the above discussion. However, it can also be seen that for any particular VB_z value there is a considerable scatter of voltage values about the mean, amounting typically to a range of about 50 kV, comparable in magnitude to the overall effect. In addition, voltages of up to about 80 kV may be observed even for IMF B_z values which are quite strongly positive (for typical solar wind speeds, $VB_z = 1$ mV m^{-1} corresponds to $B_z = 2.5$ nT). These voltages have often been ascribed to the non-reconnection "viscous" flows which may be excited in the system, but no direct observations of the boundary layer or cleft as yet indicate that so large a voltage is generated by these means, 1–10 kV being far more typical (Smiddy *et al.*, 1980; Mozer, 1984; Burch *et al.*, 1985; Mitchell *et al.*, 1987).

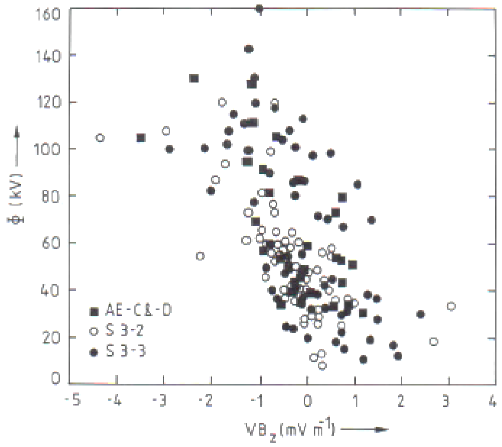

Fig. 2. Plot of the transpolar ionospheric voltage, obtained by integration of data from low-altitude spacecraft, versus the East-West component of the interplanetary electric field VB_z. The voltage values were obtained from three studies (Reiff *et al.*, 1981; Doyle and Burke, 1983; and Wygant *et al.*, 1983), and were compiled in this form by Cowley (1984)

In organizing flow and related data according to concurrent IMF data, as in Fig. 2 and the other studies cited above, the implicit assumption is being made (or hypothesis tested) that for a particular set of interplanetary conditions a particular flow pattern will emerge essentially instantaneously (or within propagation delays of a few minutes). The flow patterns shown in Fig. 1, for example, and equivalent empirical convection models, are interpreted as representing steady-state flows. However, there are two basic reasons why this description is expected to be inadequate. The first is that, whereas the direction of the IMF may be taken to form the principal determinant of magnetopause coupling processes, the action of these processes alone results in an evolving pattern of flow rather than a steady pattern, as flux is transferred from the dayside to the tail. The nature of this time-dependent flow is such that it will also lead to significant scatter in derived polar cap voltage values, as will be discussed further below. The second point is that flows are also generated by processes in the tail (e.g. during substorms), and that these may be expected to be only indirectly linked to concurrent IMF conditions near the Earth. In particular, flows generated by such means may contribute significantly to the large voltage values noted above which occur when VB_z is positive. For these reasons the IMF vector alone (or for that matter any concurrent interplanetary quantity) clearly represents an inherently inadequate quantity with which to parameterize magnetosphere-ionosphere flow.

The two-component flow model

From these considerations, and from radar studies of the ionospheric flow response to changes in the IMF, we concurr with Lockwood *et al.* (1990b) that flows in the magnetosphere-ionosphere system must be considered to consist of the sum of two intrinsically time-dependent components. One component is driven by dayside coupling and may to a first approximation be parameterized in terms of the concurrent near-Earth interplanetary conditions, principally the IMF vector. The other component is driven by tail processes and is related to the past history of the interplanetary medium and magnetosphere in a more complex manner which remains to be understood in detail. To a first approximation, however, the tail-driven flows may be also be parameterized in terms of interplanetary conditions (principally the North-South component of the IMF), but with a substantial flow response delay of about 30–60 min. relative to the IMF (Baker *et al.*, 1981, 1983; Clauer *et al.*, 1981; and Bargatze *et al.*, 1985, 1987). As a matter of practicality (but not prediction), the tail-associated flows might also be approximately parameterized by a magnetic activity index which emphasizes the effect of the nightside electrojet currents systems, as previously employed for related purposes by Holzer and Slavin (1979) and Holzer *et al.* (1986).

The form of the ionospheric flow which results from dayside reconnection acting alone ("unbalanced" dayside reconnection) is sketched in Fig. 3a, following the qualitative discussion given by Russell (1972) and the theoretical work of Siscoe and Huang (1985). For simplicity IMF B_y effects are not represented, though they have been treated theoretically by Moses *et al.* (1987, 1989). The circle in the figure represents the open-closed field line boundary which expands uniformly as the open flux in the system increases. The plasma flow crosses the boundary only in the dashed line portion of the circle which maps to the dayside neutral line (the dayside "merging gap"), and in this region the flows are strongest. Elsewhere the boundary moves exactly with the plasma flow (solid line portion of the circle). It may be noted that if the voltage (flux transfer rate) at the dayside neutral line is V, then the ionospheric voltage across the polar cap will also be close to V just poleward of the merging gap (provided it is narrow in local time), while falling continuously to $V/2$ across the centre of the polar cap, and to zero near midnight. The voltage measured by a polar-orbiting spacecraft will thus depend significantly upon its track across the polar cap, being larger for dayside passes than for nightside passes under these conditions. This effect will form one component of the scatter observed in Fig. 2 above, as previously noted by Lockwood (1991 a).

Similar remarks apply to the flow driven by unbalanced nightside reconnection, shown in Fig. 3b. Here, however, the open-closed field line boundary contracts in time and the flows are strongest on the nightside near the nightside merging gap. In general the total flow is a sum of the two components shown in the figure, depending on the concurrent values of the dayside and nightside reconnection rates. Only in the singular case where these rates are equal will a steady flow pattern prevail. In this case the transpolar voltage will be V (equal to the dayside and nightside flux transfer rates) at all positions poleward of the merging gaps.

The second effect which will produce scatter in Fig. 2 results from the expected indirect relation between the tail reconnection rate and concurrent interplanetary conditions in the near-Earth region. As mentioned above, to a first approximation the rate of tail reconnection lags behind the interplanetary input by several tens of minutes. In the simplest picture, in which we envisage a tail neutral line at a fixed location from Earth, such delays will arise inevitably from the finite information propagation speed between the subsolar region where dayside reconnection occurs and the reconnection region in the tail. Information may propagate from the dayside to the tail either inside the magnetosphere via the excitation of flow through the ring current and plasma sheet (communicated at the magnetosonic speed) or outside the magnetosphere in the solar wind via the addition of open flux tubes to the tail lobes (carried down-tail at the solar wind speed). In either case the information propagation speed will be just a few hundred km s^{-1}. Consequently, if the tail neutral line lies at a typical downtail distance of about 100 to 150 R_E, as indicated by ISEE-3 observations (Slavin *et al.*, 1985), the information propagation delay will be about 20–30 min. Furthermore, once this response has occurred, the information will propagate back to the ionosphere at a speed corresponding to the Alfven speed in the tail lobes (1000 km s^{-1}), incurring a further delay of at least 10 min (the corresponding delay for the dayside magnetopause is only about 2 min).

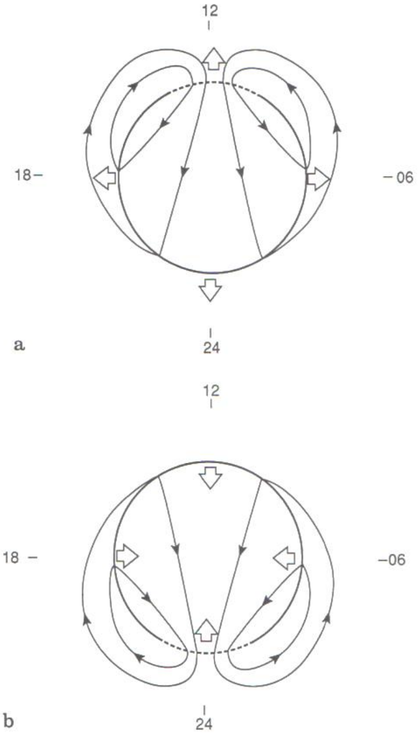

Fig. 3 a, b. Sketch showing the form of the two basic time-dependent components of the high-latitude ionospheric flow due to **a** unbalanced dayside reconnection and **b** unbalanced tail reconnection. The open-closed field line boundary is indicated by the circle, which expands outwards in **a** while contracting inwards in **b**, as indicating by the *large arrows*. In each case, the *dashed line* portion of the boundary represents the merging gap mapping to the active neutral line, where flow crosses the boundary between open and closed flux. Elsewhere the boundary moves exactly with the flow (*solid portion of the circle*)

In order to illustrate the consequences which follow directly from such delays, we consider the simplest possible ad hoc model in which we make the assumption that the reconnection rate in the tail is exactly equal to that at the dayside, but is delayed by about 30 min. The assumption of equal (but delayed) tail reconnection is made simply to isolate the effects caused by the delay alone, but could readily be generalized to include more complex relationships between the dayside and nightside reconnection rates. However, since we know that the amount of open flux in the system typically varies between only moderately different upper and lower limits, this implies that at least on average the dayside and tail reconnection rates must balance. In Fig. 4 we show the response of such a system to a typical 1-h interval of steady southward-directed interplanetary field at the magnetopause (see Rostoker *et al.*, 1988 and Hapgood *et al.*, 1991), as indicated in the top panel of the figure. The second and third panels of the figure then show the voltages associated with the dayside and nightside neutral lines respectively, which are equal to the rates of creation and destruction of open magnetic flux. We assume that the dayside voltage changes promptly from zero to V volts when the subsolar magnetosheath magnetic field changes from positive to negative, and then returns to zero when the field resumes its positive value (we thus ignore "first order" non-reconnection coupling processes). The nightside reconnection rate, in this simple illustration, is then taken to exhibit the same pattern, but with an approximate 30-min delay. Consequently, the system exhibits a 30-min interval of unbalanced dayside reconnection after the IMF turns south, followed by 30 min of balanced dayside and tail reconnection, and then 30 min of unbalanced tail reconnection after the IMF turns northward near the Earth. The fourth and fifth panels then show the amount of open flux in the system and the voltage across the central polar cap, respectively. The latter is given by the arithmetic mean of the dayside and nightside voltages, assuming that the polar cap remains circular (Lockwood, 1991 a). The polar cap voltage also includes the effect of the additional propagation delay from the reconnection regions to the ionosphere, and the finite time scale for system response, which is shown in the following section to be about 15 min. During the period of unbalanced dayside reconnection the amount of open flux increases linearly with time at the rate V Wb s^{-1}, and the voltage across the central polar cap, is $V/2$ volts (after allowing for propagation and response delays). In the following interval of balanced reconnection the amount of open flux is steady and the polar cap voltage is V. During the subsequent period of unbalanced tail reconnection the amount of open flux decreases at the rate V Wb s^{-1} to its initial value, and the polar cap voltage returns to $V/2$ before becoming zero again after tail reconnection has ceased. These results thus illustrate in a simple way the inherent inadequacy of using only the IMF to parameterize the flow, either in terms of the size or the strength of the flow system. The results also show how large voltages can and do occur during intervals of positive IMF B_z due to continued reconnection in the tail. Furthermore, it is striking how such a simple system will automatically exhibit "growth", "steady-state", and "decay" phases in response to a simple approximately 1-h pulse of southward IMF. To mimic a "substorm expansion" we would only need to assume that the tail reconnection rate, once excited, exceeds that at the dayside, so that the open flux then decreases. However, we need to recognize that in this case the excitation of tail reconnection may involve the formation of a new near-Earth neutral line (Russell an McPherron, 1973; Hones, 1979), such that the delay time for tail response would then be related to the time required for the system to reach instability during the "growth phase", rather than the time required for the far-tail reconnection region to respond. The actual response of the tail system remains one of the major areas of uncertainty in these considerations.

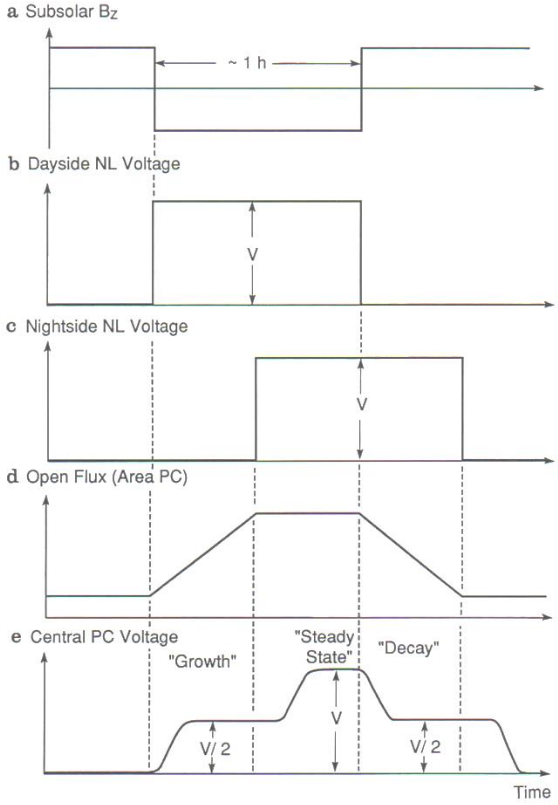

Fig. 4a–e. Sketch showing the magnetosphere response to a 1-h interval of southward IMF at the subsolar magnetopause, for the simple case in which the nightside reconnection voltage follows the dayside reconnection voltage, but with a 30-min delay corresponding to the information propagation time to a distant (100 R_E) tail neutral line. The graphs show: **a** the assumed subsolar interplanetary magnetic field; **b** the voltage along the dayside neutral line; **c** the voltage along the tail neutral line; **d** the open flux in the system [equivalent to the area of the polar cap (PC)]; **e** the voltage across the central polar cap at ionospheric heigths assuming a circular expanding or contracting polar cap, and also allowing for finite information propagation from the reconnection regions to the ionosphere

The excitation and decay of flow

The two-component flow picture discussed in the previous section shows that it is not the existence of open flux in the system, as such, which generates flow, but rather the creation of new open flux on the dayside and the destruction of old open flux in the tail. There is therefore no necessary connection between the electric field in the solar wind at one of an open flux tube and the electric field in the ionosphere at the other, except in an average sense. Only in the singular steady-state case of balance dayside and tail reconnection will the internal electric field represent a simple mapping along open field lines of the interplanetary electric field lines of the interplanetary electric field (assuming zero field-aligned voltage drops). On the other hand, if we were able to switch off both dayside and tail reconnection (and all other coupling processes as well), then flow in the system would cease irrespective of the amount of open flux present.

We thus envisage the existence of a zero-flow equilibrium magnetosphere containing an arbitrary tail of open flux extending (in principle) to infinity. We emphasize that for a number of reasons this system may not be physically realizable. In particular, it may be expected that reconnection will occur in some regions of the magnetopause for any orientation of the IMF, thus exciting flow in the interior. Even if this is not the case, other "viscous" magnetopause coupling processes will still be present to some degree. In addition, the mere existence of an open tail may actually require the presence of tail reconnection at some level, in order to maintain the tail current system. Dungey (1972) has provided an argument which indicates that this may be the case. Nevertheless, the concept of a zero-flow equilibrium magnetosphere is very important, since it represents a system which we can perturb to excite internal flow, and to which the system will subsequently decay, but with a changed amount of open flux. The point can be illustrated with reference to Fig. 5. Suppose we start with a zero-flow equilibrium in which open flux F is present. We represent the open-closed field line boundary in the ionosphere in this case by the solid circle in Fig. 5a. We then perturb the system with an impulsive dayside reconnection event – a flux transfer event (FTE) – which produces an increment in the open flux dF, such that the open-closed field line boundary is impulsively displaced equatorward in the noon sector, as shown by the solid line in Fig. 5b. (Note that for reasons of clarity the perturbation of the system is drawn unrealistically large in the figure, since Lockwood *et al.* (1990b) have estimated that the largest observed FTEs correspond to a $\mathrm{d}F/F$ of about 0.03). The new zero-flow equilibrium open-closed field line boundary corresponding to the new amount of open flux $F+\mathrm{d}F$ is then represented by the dot-dash circle in Fig. 5b, and is such that the actual open-closed field line boundary after the impulse lies equatorward of the latter in the perturbed noon sector, and poleward thereof elsewhere. Flow will then be excited which moves the perturbed system towards the new equilibrium configuration, as shown in Fig. 5c (Freeman and Southwood, 1988), and when that has been achieved the flow will stop. The new open flux will then be located in the polar cap just poleward of the position where it was created, as shown in Fig. 5d, and it will remain there until the next impulse occurs.

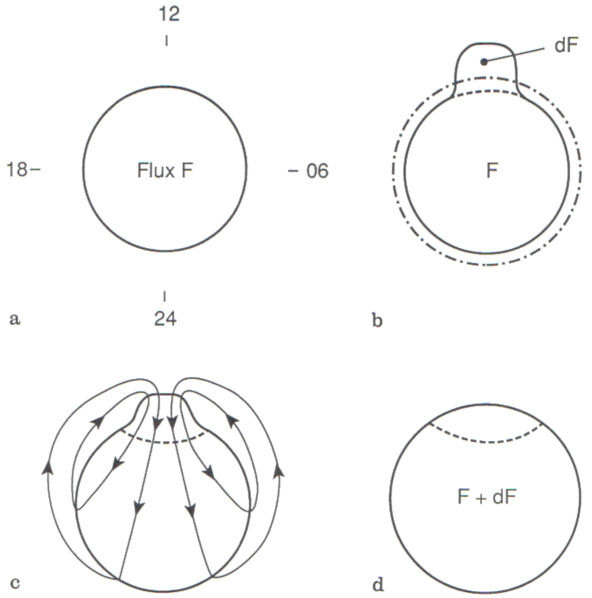

Fig. 5a–d. Sketch illustrating the response to an impulse of dayside reconnection: **a** initial zero-flow equilibrium configuration with open flux F, the *solid line* indicates the open-closed field line boundary; **b** perturbed boundary (*solid line*) following the impulse, together with the new zero-flow equilibrium boundary (*dot-dash line*) which contains the same amount of open flux $F+\mathrm{d}F$; **c** form of the flow which takes the perturbed system towards the new zero-flow equilibrium configuration, following Fig. 3a; **d** new zero-flow equilibrium with flux $F+\mathrm{d}F$, the *dotted line* indicates the boundary of the open flux created during the impulse

The corresponding flows in the magnetosphere are sketched in Fig. 6. Figure 6a shows conditions in the equatorial plane just after the reconnection impluse has occurred. The magnetopause boundary is eroded in the region where the newly-opened flux has been removed towards the tail, and is no longer in equilibrium with the magnetosheath plasma pressure. The field lines thus move outward in this region, and inward elsewhere in the near-Earth system until equilibrium has been restored. This motion corresponds to the ionospheric flow on closed flux tubes shown in Fig. 5c. Similarly, Fig. 6b shows conditions in a cross section through the tail. The addition of new open flux to the tail increases both the normal and tangential stresses exerted by the solar wind. The tangential stress is eventually communicated to the Earth via the force exerted on the Earth's dipole by the tail field system. The normal stresses push the new open tube into the lobe as shown in the figure, such that the field lines move into the lobe in the vicinity of the perturbed region, and outward elsewhere (as also shown in the tailward portion of Fig. 6a). This motion corresponds to the ionospheric flow on open flux tubes shown in Fig. 5c.

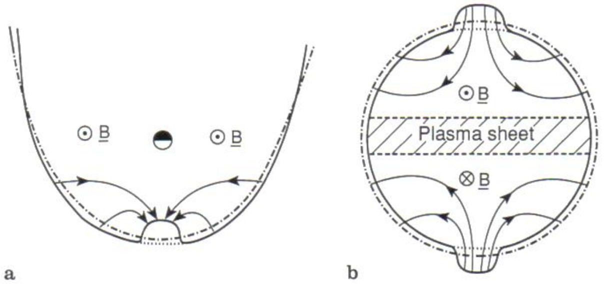

Fig. 6 a, b. Sketch of the magnetospheric flow excited by a dayside reconnection impulse, corresponding to the ionospheric flow show in Fig. 5: **a** in the equatorial plane, the *solid line* shows the magnetopause after the impulse, the *dot-dash line* the new equilibrium magnetopause; **b** in a cross-section through the tail

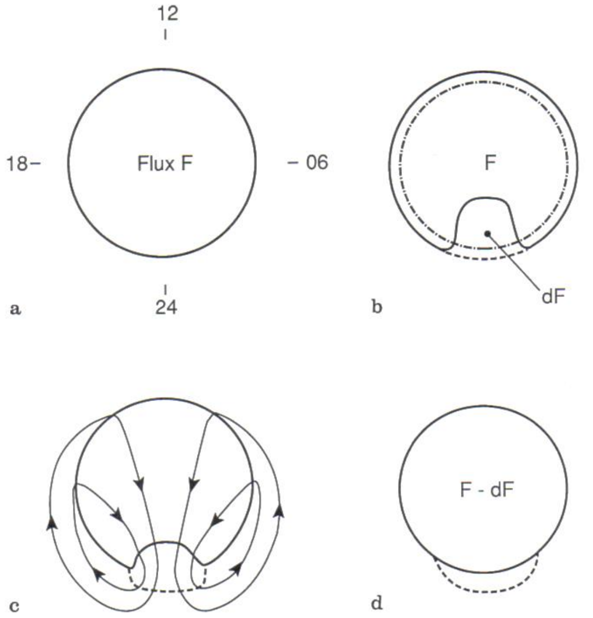

Fig. 7 a–d. Sketch illustrating the response to an impulse of tail reconnection: **a** initial zero-flow equilibrium configuration with open flux *F*, the *solid line* indicates the open-closed field line boundary; **b** perturbed boundary (*solid line*) following the impulse, together with the new zero-flow equilibrium boundary (*dot-dash line*) which contains the same amount of open flux *F*−d*F*; **c** form of the flow which takes the perturbed system towards the new zero-flow equilibrium configuration, following Fig. 3 b; **d** new zero-flow equilibrium with flux *F*−d*F*, the *dotted line* indicates the boundary of the flux which was closed during the impulse

Similar considerations also apply to impulsive tail reconnection, as shown in Fig. 7, which has the same format as Fig. 5. In this case, however, the impulsive reconnection event decreases the amount of open flux in the system.

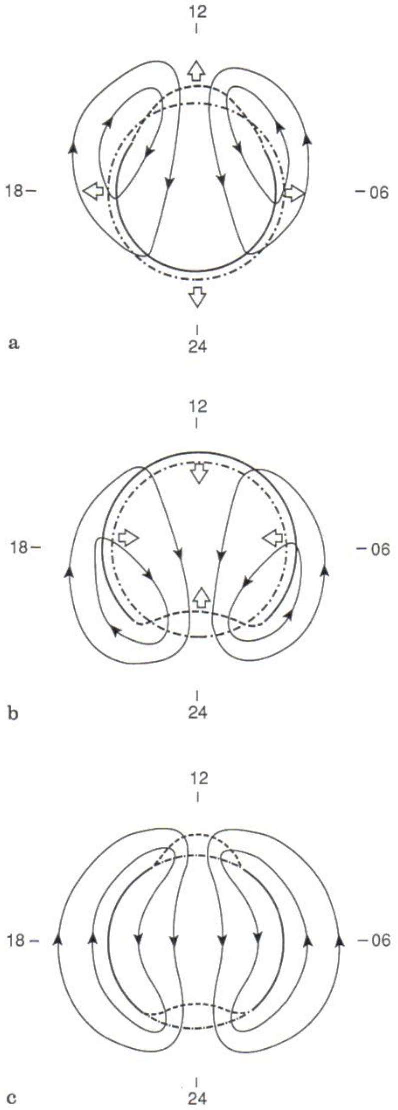

Fig. 8 a–c. Interpretation of the flows driven by **a** steady unbalanced dayside reconnection and **b** steady unbalanced nightside reconnection, previously shown in Fig. 3, in terms of the zero-flow equilibrium boundary picture. In each case the *dashed line* corresponds to the merging gap, the *solid line* to the open-closed field line boundary which moves with the plasma flow, and the *dot-dashed line* to the zero-flow equilibrium boundary which instantaneously contains the same amount of open flux. The *large arrows* indicate the sense of motion of these boundaries. **c** The steady-state flows driven by balanced dayside and nightside reconnection in the same format

We may apply similar ideas to continuous reconnection as well, as sketched in Fig. 8 a and b for the two basic components of the ionospheric flow, corresponding to unbalanced dayside and tail reconnection respectively. In these cases the instantaneous open-closed field line boundary consists of two portions. The dashed-line "merging gap" portion maps to the active neutral line where the instaneous flow crosses the boundary, and the solid line portion to where the boundary moves exactly with the flow (in agreement with the format of Fig. 3). The dot-dashed line also shows the instantaneous zero-flow equilibrium boundary, which by definition contains the same amount of open flux, and toward which the system will move via the excitation of flow. In the case of unbalanced dayside reconnection both of these boundaries expand outwards as the open flux increases, while for unbalanced tail reconnection they both contract as the open flux decreases. For dayside reconnection the actual open-closed field line boundary lies equatorward of the instantaneous equilibrium boundary in the vicinity of the merging gap, and poleward elsewhere. Conversely, for tail reconnection the open-closed field line boundary lies poleward of the equilibrium boundary in the vicinity of the merging gap, and equatorward elsewhere. These displacements between the actual boundaries and the zero-flow equilibrium boundaries represent the potential in the system for flow. When reconnection starts, the system becomes displaced from its equilibrium configuration and flow becomes excited, moving the system back towards equilibrium. When reconnection stops, the system moves from the then-existing non-equilibrium configuration back to the equilibrium configuration corresponding to the existing quantity of open flux, after which flow ceases.

In the general case in which the dayside and nightside voltages are both non-zero, the flow configuration will correspond to an appropriate combination of the patterns shown in Fig. 8a and b, the overall pattern either expanding or contracting depending on which voltage is larger. The special steady-state case of equal voltages is illustrated in Fig. 8c. In this case the actual open-closed field line boundary lies equatorward of the zero-flow equilibrium boundary in the dayside merging gap, poleward of the latter in the nightside merging gap, while the boundaries are coincident elsewhere.

The time scale on which the flow is excited and decays can be obtained observationally from estimates of the typical displacements between the actual open-closed field line boundary and the zero-flow equilibrium boundary in the ionosphere, and the observed north-south components of the flow. If we consider typical North-South motions of the dayside cusp or the typical extent of the auroral substorm bulge, then it seems reasonable to estimate the typical North-South displacements to be a few degrees of latitude, corresponding to a few hundred km. If we then take the North-South flow to be a few hundred m s^{-1}, as typically observed, then the time scale will be of the order of 1000 s, i.e. about 15 min. We emphasize that this represents the time scale for the full excitation and full decay of the flow systems shown in Fig. 8. However, these processes will begin as soon as the information that the reconnection change has taken place reaches the ionosphere. These conclusions are wholly compatible with the results on the excitation and decay of the flow which have been derived from high time-resolution radar flow measurements, as mentioned in the introduced (Rishbeth *et al.*, 1985; Etemadi *et al.*, 1988; Todd *et al.*, 1988). Indeed, it was the consideration of the implications of those measurements which led us to develop the conceptual picture presented in this paper.

We now consider the physical interpretation of the time scale estimated above. If we take the dayside flow system, for example, the discussion is in two parts. The first is the time scale for newly opened flux tubes produced at the dayside magnetopause to evolve into the tail i.e. the time scale for the boundary conditions to change in response to a reconnection event. The important point here is that we need consider the motion of a "new" open tube only until it has been carried a few tens of R_E into the tail, the distance corresponding to the overall spatial scale of the near-Earth magnetic field system. The further stretching of the tube down-tail produces little subsequent change in the near-Earth field system, and consequently will excite little more flow. The time scale involved is thus a few tens of R_E divided by a few hundred km s^{-1}, i.e. approximately 10 min. In colloquial terms, "new" open flux becomes "old" open flux on this time scale. The second part of the argument then concerns the time scale of the interior open and closed flux regions to respond to the change in the boundary conditions in the manner depicted above in Fig. 6. Again, simple estimates (e.g. of the time scale for information to propagate through the near-Earth system) indicate that a time scale of 5–10 min is involved. Overall, therefore, the approximately 15-min time scale estimated above appears to have a reasonable physical basis.

Additional complications

In this section, we finally consider some additional complicating factors not explicitly discussed above i.e. the effects which are associated with IMF B_y, with IMF B_z positive, and with "viscous" (non-reconnection) coupling at the magnetopause.

We begin by showing in Fig. 9 the response in the Northern hemisphere to a dayside reconnection impulse when IMF B_y is positive, in the same format as Fig. 5. The new factor entering here is the East-West tension force acting on newly opened dayside flux tubes, which causes them to flow longitudinally (westward in this case) before moving latitudinally into the polar cap. This gives rise to a flow pattern which is asymmetrical about noon, as shown in Fig. 9c, and the new open flux tubes experience a net IMF B_y-dependent displacement in local time before coming to rest in the new equilibrium polar cap (Fig. 9d). The time scale for this motion should correspond to the approximately 15-min interval discussed above. We suggest that this behaviour is directly related to the "dayside auroral break-up" phenomenon discussed, for example, by Sandholt *et al.* (1990) and Lockwood *et al.*, (1990a).

Turning now to the flows driven by continuous dayside reconnection, in Fig. 10a and b we show the patterns in the northern hemisphere which correspond to IMF B_y positive and negative respectively, in the same format as Fig. 8a. In addition to the asymmetrical flows mentioned above, two other effects are illustrated: first,

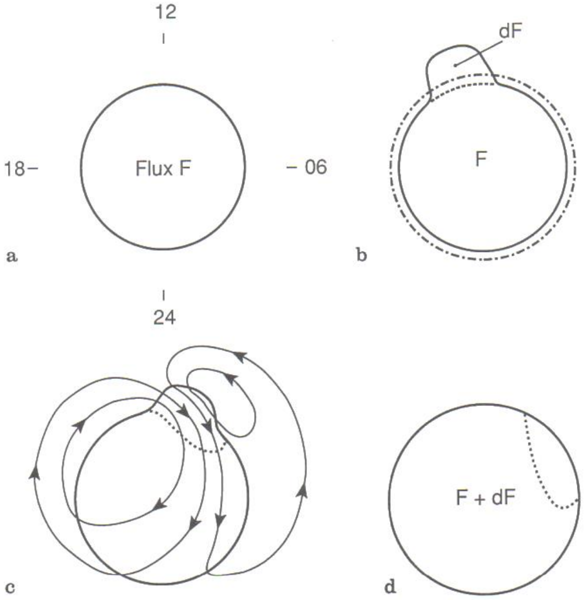

Fig. 9 a–d. Sketch illustrating the response to an impulse of dayside reconnection, as in Fig. 5, but now including the effect of IMF B_y (positive of the Northern hemisphere): **a** initial zero-flow equilibrium configuration with open flux F, the *solid line* indicates the open-closed field line boundary; **b** perturbed boundary (*solid line*) following the impulse, together with the new zero-flow equilibrium boundary (*dot-dash line*) which contains the same amount of open flux $F+\mathrm{d}F$; **c** form of the flow which takes the perturbed system towards the new zero-flow equilibrium configuration, now including the effect of the East-West tension on the open flux tubes; **d** new zero-flow equilibrium with flux $F+\mathrm{d}F$, the *dotted line* indicates the boundary of the open flux created during the impulse showing its net displacement in local time

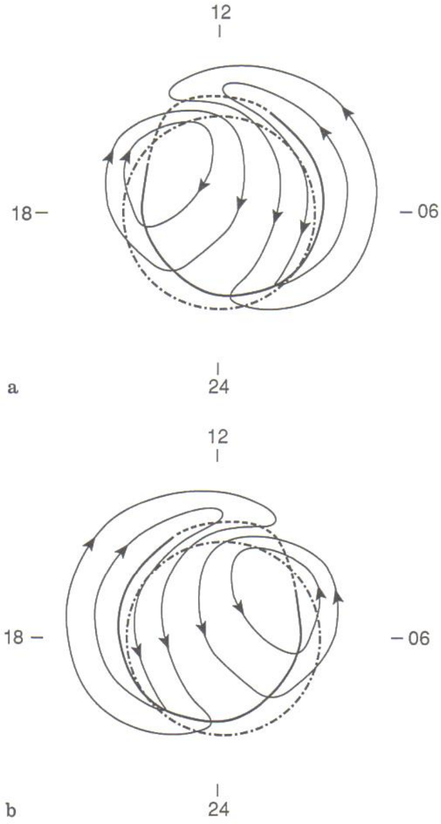

Fig. 10 a, b. Sketch of the flows driven in the Northern hemisphere by steady unbalanced dayside reconnection in the format of Fig. 8 a, for **a** positive IMF B_y and **b** negative IMF B_y

the local time displacement of the merging gap region in the direction of IMF B_y; and second, the opposite displacement of the remainder of the boundary due to the azimuthal motion of the new open flux tubes shown previously in Fig. 9. Since the corresponding displacements in the southern hemisphere must simultaneously be in opposite directions, these effects imply the existence of distortions of the magnetic field in the closed field line region of the magnetosphere. These distortions are of the form that would result from a partial penetration of IMF B_y into this region (Cowley, 1981; Cowley and Hughes, 1983). They arise from the IMF B_y-dependent asymmetrical evolution of the open flux tubes over the dayside magnetopause and their asymmetrical addition to the tail lobes, which result in asymmetrical forces being exerted on the magnetosphere, as discussed further by Cowley *et al.* (1991).

If we now consider the response to a sudden change in the sense of IMF B_y, we would expect that the East-West flow in the equatorward part of the cusp would respond promptly to the change in the sense of the East-West stress exerted on the new open flux tubes, while in the poleward region the flow asymmetry would continue to reflect the sense of the previous period of IMF B_y. Greenwald *et al.* (1990) have observed such changes simultaneously in both hemispheres using the conjugate PACE radars. However, the effect of the East-West stresses lasts only for an interval of about 10–15 min on given open flux tubes while they are evolving over the near-Earth magnetopause and before they are swept by the super-Alfvenic magnetosheath flow into the more distant tail. Consequently, the flow asymmetry corresponding to the previous direction of IMF B_y will die away on time scales of about 10–15 min, to be replaced over the whole polar cap by the asymmetry corresponding to the new sense of IMF B_y. This conclusion holds despite the fact that after about 15 min most of the open flux present would still remain connected to a B_y field of the opposite polarity. The new flow asymmetry is enforced on the "old" open flux tubes in the near-Earth tail lobe by the asymmetric addition of the "new" open flux tubes to the tail lobes on the above 10–15-min time scale. This will then produce a "new" asymmetric flow throughout the near-Earth tail lobe, and in the polar cap, as can readily be seen from a simple modification of Fig. 6.

In this paper we have so far been concerned mainly with the flows driven by reconnection processes occurring either at the magnetopause or in the tail plasma sheet.

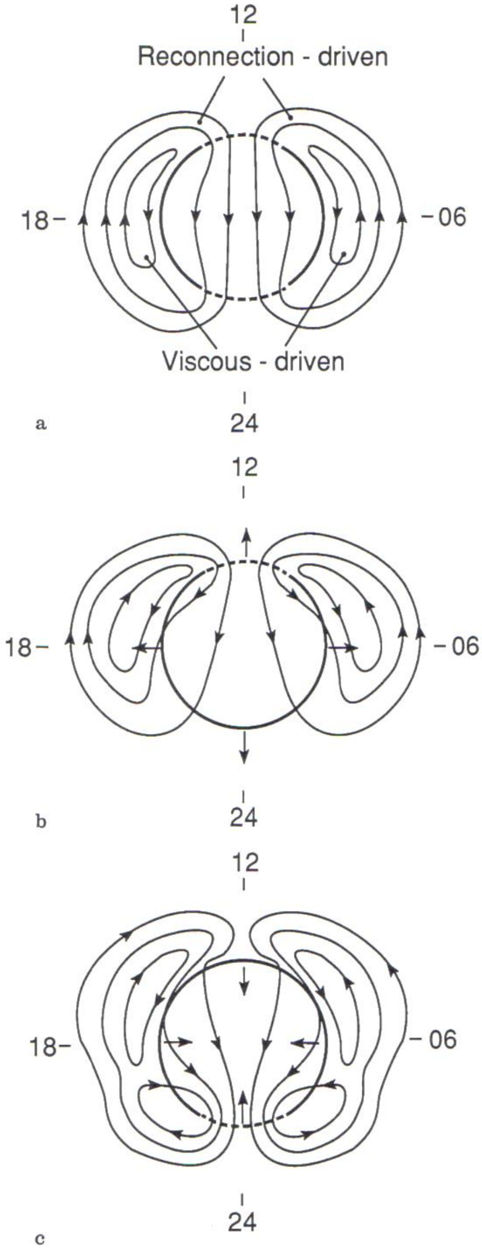

Fig. 11 a–c. Sketches showing the effect of "viscously" driven flow on the usual two-cell convection pattern. In each case the *circle* represents the open-closed field line boundary (the *dashed lines* are merging gaps and the *solid lines* the regions where the boundary moves exactly with the flow), and the *short arrows* show its direction of motion. The sketches represent **a** balanced dayside-nightside reconnection; **b** unbalanced dayside reconnection; **c** unbalanced nightside reconnection

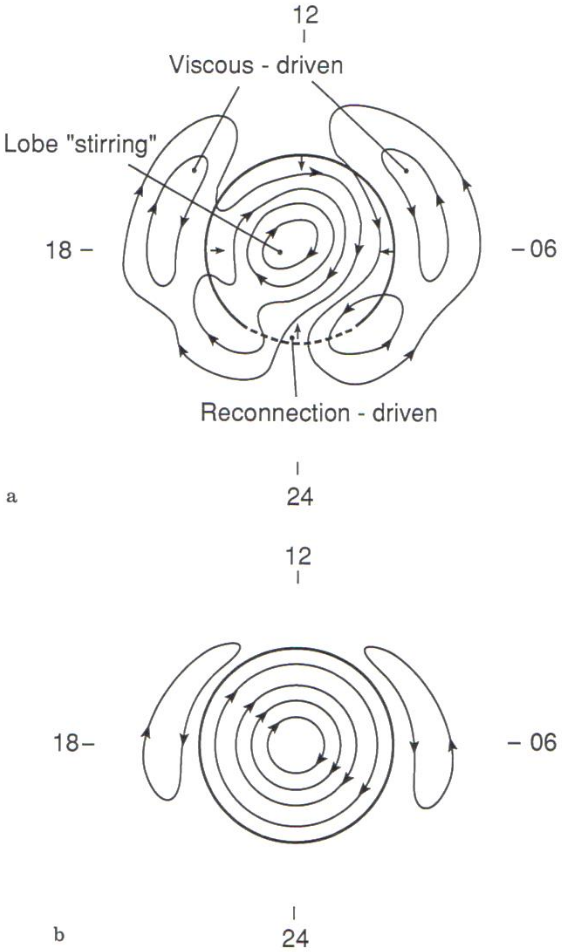

Fig. 12 a, b. Sketch of the high-latitude ionospheric flow in the Northern hemisphere for northward-directed IMFs and with IMF B_y positive, in the same format as Fig. 11. In **a** contributions to the flow are present due to non-reconnection "viscous" coupling at the magnetopause boundary, continued weak tail reconnection, and lobe "stirring" due to reconnection between the IMF and open lobe flux. **b** shows the reduced flow system which occurs in the complete absence of tail reconnection.

However, flows may also be driven by "viscous" processes as well, and we therefore briefly consider how these may also complicate the picture presented above. In principle, "viscous"-driven flows may be considered in exactly the same way as for the reconnection-driven flows discussed above, i.e. in terms of flow patterns associated with flux transfer to and from the tail, which, in general, will co-exist with the reconnection-driven flows. Sketches of the combined flow under usual conditions are shown schematically in Fig. 11. The central circle in each of these sketches represents the open-closed field line boundary, where the dashed line represents the merging gap and the solid line the region where the boundary moves exactly with the flow. The short arrows also show the direction of motion of the boundary. Figure 11 a represents the steady-state case of equal flux transport to and from the tail. The cells of flow driven by reconnection and by the viscous process are clearly delineated, though of course, in regions which map near the magnetopause boundary the flow may influenced by the combined action of both processes. Figure 11 b shows the modified picture for unbalanced dayside reconnection. Here we note the presence of some streamlines which cannot be assigned either to reconnection- or viscously-driven flow cells, but which are strongly influenced by both processes on differing sections of their length. It is also possible for multi-cell flows to occur under these conditions, as illustrated for the case of unbalanced tail reconnection in Fig. 11 c. Patterns resembling the latter case have recently been derived from combined radar and magnetometer data by Knipp *et al.* (1991), during a period of flow reconfiguration following a southward-to-northward change in the IMF.

Finally, in Fig. 12, we illustrate the flows which will occur for strongly positive IMF B_z. The discussion given in the previous sections (e.g. in relation to Fig. 4) would indicate that under these conditions the flow will decay to zero on a relatively short time scale. However, following the above discussion this will not be the case for a number of reasons. Figure 12 a illustrates the complex flows which may occur under these conditions due to the combined action of three comparable components, namely "viscous" coupling at the magnetopause, lobe "stirring" due to reconnection between the northward IMF and open tail lobe flux tubes discussed previously, and continuing weak tail reconnection. It may be noted that with a tail neutral line voltage of 10 kV, say, it would take a significant fraction of a day to destroy all of the open flux present in a normal tail. Such prolonged periods of northward IMF are very rare (Rostoker *et al.*, 1988; Hapgood *et al.*, 1991). However, if the tail reconnection rate does drop to zero, the flow pattern will reduce to that shown in Fig. 12 b, i.e. the sum of flows due to viscous coupling and lobe stirring only. Thus there are a number of ways in which the simple initial picture presented above can become complicated in practice.

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