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TIME-DEPENDENT FLOWS IN THE COUPLED SOLAR WIND–MAGNETOSPHERE–IONOSPHERE SYSTEM

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ABSTRACT

Concepts of time-dependent flow in the coupled solar wind-magnetosphere-ionosphere system are discussed and compared with the frequently-adopted steady-state paradigm. Flows are viewed as resulting from departures of the system from equilibrium excited by dayside and nightside reconnection processes, with the flows then taking the system back towards a new equilibrium configuration. The response of the system to reconnection impulses, continuous but unbalanced reconnection and balanced steady-state reconnection are discussed in these terms. It is emphasized that in the time-dependent case the ionospheric and interplanetary electric fields are generally inductively decoupled from each other; a simple mapping of the interplanetary electric field along equipotential field lines into the ionosphere occurs only in the electrostatic steady-state case.

TIME-DEPENDENT FLOWS

Much of the past and present discussion of flows within the coupled solar wind-magnetosphere-ionosphere system has been in terms of steady-state convection, albeit modulated by interplanetary and substorm conditions. Despite this there are compelling reasons to consider explicitly the time-dependence of the flow. First, the coupling processes at the magnetopause are often impulsive in character giving rise to flux transfer events (FTEs) /1,2/, as are the substorm-related relaxation processes in the tail /3-5/. Second, even if integration over the magnetopause impulses can be considered to provide a steady flux transfer to the tail during a particular interval, there is no guarantee that the tail will respond to provide an essentially steady balancing return, both because of the finite communication time between the dayside and the tail and possible time scales inherent to the latter. Indeed, a central concept in substorm physics concerns an unbalanced transfer of open flux to the tail during the growth phase and its subsequent return during expansion and/or recovery /6/. Third, it is well established that the ionospheric flow responds strongly to the direction and strength of the interplanetary magnetic field (IMF) /7-9/, and it is of interest to consider how the system responds when the IMF changes. For these reasons it is necessary to consider how flows vary on time scales from minutes to many tens of minutes, scales which are much shorter than the overall cycle time of flux transport in the system, which is typically several hours. The discussion in this paper attempts to give a succinct presentation of the concepts of time-dependent flow first advanced by Cowley and Lockwood /10/. The discussion is principally in terms of Dungey's open model /11/, since observations over the past 30 years have indicated the dominance of the reconnection process in governing solar wind-magnetosphere coupling. Nevertheless with some modification the central concepts advanced here could be applied to any coupling mechanism.

In a steadily-convecting magnetosphere there are two main ways in which the flow in the system has been viewed. The first considers the flux transfer in the system i.e. the rate of steady transfer of open flux to the tail lobes resulting from dayside reconnection and its return to the dayside through the central magnetosphere following reconnection in the tail. This flux transfer rate is exactly equivalent to the steady voltage across the system (1 volt = 1 Wb s^{-1}), which, in the absence of field-aligned electric fields (as assumed throughout here), is also equal to the voltage between the foci of the twin-cell flow at ionospheric heights. The second way is to view the electric field in the region of open flux tubes as the image of the interplanetary electric field mapped along equipotential field lines into the tail lobes and down to the ionosphere /12/. This follows from the fact that in the steady state the electric field is curl-free from Faraday's law and hence can be expressed in terms of a scalar potential, and the field lines are equipotentials if the parallel electric field is zero. The flow of closed field lines may then be considered as a response to this boundary condition.

In the time-dependent case, however, the latter description of the flow is in general no longer valid. The flows can still be discussed in terms of the flux transfers in the system, to and from the tail, but the electric field on open field lines inside the magnetosphere and ionosphere can no longer be viewed simply as a mapping of the interplanetary electric field even if the field-aligned electric field remains zero. This follows directly from the fact that in the general case we may expect the magnetic structure to vary with time, as discussed further below, so that the electric field will have a curl and cannot be simply described in terms of a scalar potential which can be mapped along field lines.

As a simple example, consider the idealized problem of an initially steady-state open magnetosphere containing a certain quantity of open flux in which at some instant of time all reconnection processes are switched off for an indefinite period, both at the magnetopause and in the tail. The amount of open flux in the system thus remains constant after this time. If the solar wind electric field were to continue to map into the ionsopheric polar caps giving flow there at 500 m s^{-1}, say, then the open flux regions would migrate to the nightside equator in only ~ 4 h ! This is obvious nonsense. Instead, it is evident that after the "ends" of the most recently-opened field lines have been carried more than several tens of Earth radii down the tail, the near-Earth system will approach an equilibrium whose form will depend upon the amount of open flux present, but not upon the details of its further extension downstream by the flow. As this near-Earth equilibrium is approached the flow in this region will die away. In other words the electric field in the near-Earth region will decay towards zero despite the fact that the interplanetary electric field continues to exist undiminished at the tailward end of the open flux tubes. As time proceeds, therefore, the near-Earth electric field will continuously depart from the initial electrostatic mapping of the interplanetary electric field as it decays. We strongly emphasize that this does not imply or require the development of field-aligned electric fields between the two regions; rather the electric field becomes inductive in nature associated with the changing magnetic structure. The latter changes are simply associated with the extension of the tail to larger and larger distances as the open tubes attached to the Earth are carried downstream by the solar wind flow. As time goes on an equilibrium tail configuration is established at increasingly large distances downstream from the Earth.

As a second example we contrast conditions in a steadily convecting magnetosphere driven by steady balanced reconnection at the dayside and in the tail, with a system with an identical mean flux transfer rate which is instead driven by pulsed reconnection in which the reconnection rate is X times the previous value but occurs for only X^{-1} of the time. In the latter case the normal component of the magnetic field threading the magnetopause and the tangential component of the electric field are X times that in the steady model but are present over only X^{-1} of the surface. If the frequency with which the pulses of reconnection occur is allowed to become very large then it is obvious that the flow and electric field in the interior of the system will be essentially identical to that in the strictly steady case, determined by the mean rate of flux transfer in the system. However, since the tangential electric field at the magnetopause on each open flux tube is now X times the previous value, the interior electric field and flow would also be X times the latter value if the electric field were simply to be mapped electrostatically.

These idealized examples should be sufficient to indicate that while the flow in the system in the general time-dependent case can be directly related to the rates of production and destruction of open flux, and the consequent rates of flux transfer to and from the tail, the steady-state concept of mapping the interplanetary electric field along equipotential field lines is not transferrable to the general case. In general the interplanetary and magnetosphere-ionosphere electric fields are inductively decoupled, meaning that the electric field in general has a curl which is directly related to time-dependent changes in the magnetic structure.

Direct observational evidence showing this decoupling of the electric fields has recently been provided by studies of an interval of prolonged northward IMF during the passage of an interplanetary magnetic cloud over the Earth /13/. In one hemisphere vigorous sunward convection was observed in the polar cap, indicating the presence of lobe reconnection on open magnetic field lines. The other polar cap, however, became almost completely stagnant, despite the presence of open flux which must experience the interplanetary electric field outside the magnetosphere.

DAYSIDE IMPULSE RESPONSE

In the first thought-experiment discussed above we concluded that in the absence of dayside and nightside reconnection (i.e. for zero flux transfer) the near-Earth system would approach an equilibrium configuration in association with the decay of the near-Earth flow, despite the continued presence of open flux in the system. This conclusion is of central significance because we can then view the production of open flux at the magnetopause and its transfer to the tail, and the destruction of open flux in the tail and its transfer to the quasi-dipolar magnetosphere, as effects which perturb the system away from such equilibria, to which the system will subsequently return (with a changed amount of open flux) via the excitation of flow.

Let us thus consider the effect of a single pulse of dayside reconnection. Suppose the magnetosphere contains open flux F and is initially in a quiescent state with low flows (i.e. is initially close to equilibrium). A pulse of reconnection then occurs at the dayside magnetopause which rapidly produces a quantity dF of open flux, which evolves over the magnetopause under the combined action of field tension and magnetosheath flow and is transferred to the tail. The removal of flux dF from the dayside perturbs the equilibrium of the closed flux tube region and excites flow until equilibrium is restored, associated with erosion of the dayside magnetopause (Fig. 1a). Similarly the addition of open flux dF to the lobes will also excite flow throughout the tail as it is assimilated under the action of magnetosheath stresses, associated with some combination of expansion of the tail radius and compression of the tail flux (Fig. 1b). These flows act to restore the near-Earth system to equilibrium with the changed amount of open flux, and as the new equilibrium is approached the flow will decay to small values. Of course, the electric field is not then zero everywhere in the system, since as the new open tube is transported antisunwards the more distant portions of the existing tail become perturbed sequentially, with flow being excited for an interval until they too approach equilibrium with the new amount of open flux. However, our interest centres here on the flow in the near-Earth magnetosphere and ionosphere, and we stress that once this region has accommodated to the change in flux and has approached equilibrium it is immaterial that the end of the new open tube continues to be stretched out further downsteam into the far distant tail since this motion does not further change conditions in the near-Earth system.

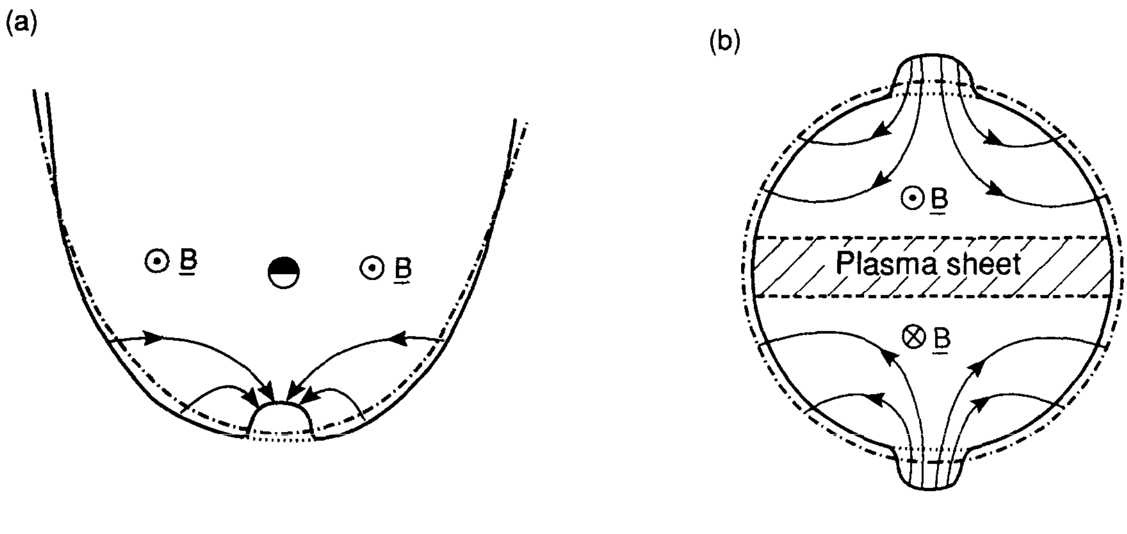

Fig.1. Magnetospheric flows excited by a pulse of dayside reconnection, (a) in the equatorial plane of the closed field line dayside region, and (b) in a cross-section through the geomagnetic tail (from /10/).

The time scale for the excitation and decay of flow in the near-Earth region due to the reconnection pulse can be considered as an amalgam of two intervals. The first is the time taken by the open tube to evolve over the dayside magnetopause and into the tail (to distances, say, of 20-30 R_E downtail), which is typically an interval of ~ 10 min. The second is the response time of the open and closed flux regions to the change in the boundary conditions, which is at least of order an Alfven wave transit time across the system, which is again 5-10 min. Of course, these times occur in parallel rather than in series so it appears reasonable to conclude that the overall time scale should be ~ 15 min.

The corresponding ionospheric flows are shown in Fig. 2. Sketch (a) shows the initial equilibrium situation with open flux F bounded by the solid line (shown conventionally as a circle) and no flow. In sketch (b) the pulse of dayside reconnection has appended flux dF (of exaggerated size) to the equatorward border of the open field region near noon; the equilibrium position of the boundary with the new amount of open flux $F + dF$ is shown by the dot-dashed circle. We assume in this idealised case that flux dF is opened so rapidly that no flow has yet commenced in sketch (b). Twin-vortical flow is then excited as in sketch (c) (the ionospheric image of the flows shown in Fig. 1), which carries the perturbed system towards the new equilibrium, after which the flows die away with the patch of new open flux assimilated into the dayside open flux region (sketch (d)). The flows shown in sketch (c) are excited first in the vicinity of the patch of new open flux near noon, and then spread to dawn and dusk and to the nightside on the ~ 10-15 min timescale discussed above, as directly observed by radar experiments and in ground-based magnetometer data /8,9,14,15/. The corresponding phase speed in the ionosphere is ~ 3-5 km s^{-1}. We should mention here that although this picture of flow excitation was first proposed in this form by Cowley and Lockwood /10/, similar concepts were implicit in earlier work by Freeman and Southwood /16/.

The impulse response of the system outlined above is a reasonable starting-point for considering the flows excited by magnetopause FTEs. However, the picture we have presented so far is valid only for the special case of a southward-pointing IMF. In general we must also include the effects associated with the east-west (y) component of the IMF as shown in Fig. 3. In this case the behaviour of the flow response can be divided into two contiguous phases. In the initial phase shown in sketch (a) the open tube evolves over the dayside magnetopause mainly under the action of the field tension and is consequently pulled

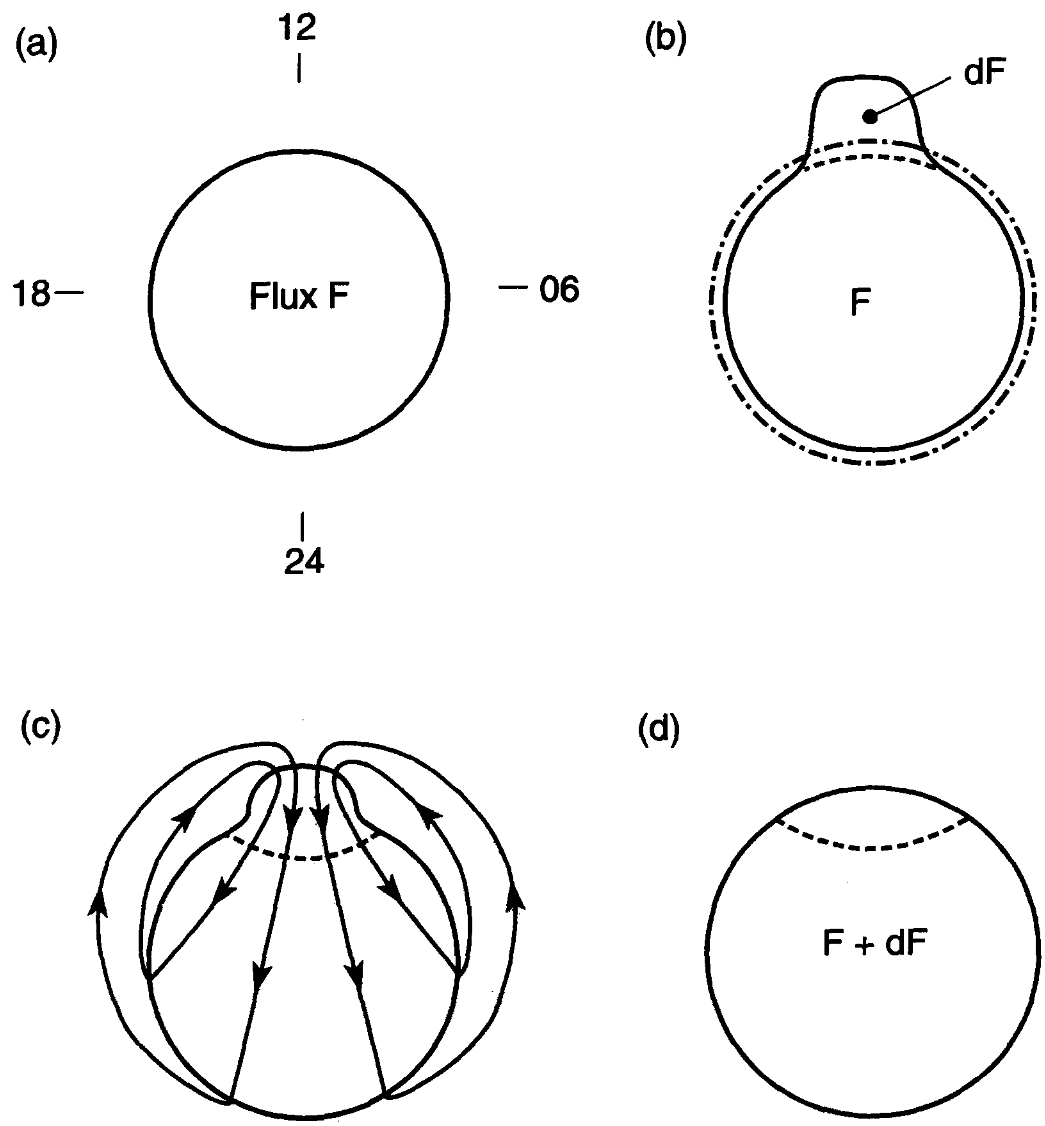

Fig.2. Response of ionospheric flow to a pulse of dayside reconnection (for southward IMF); see text for details (from /10/).

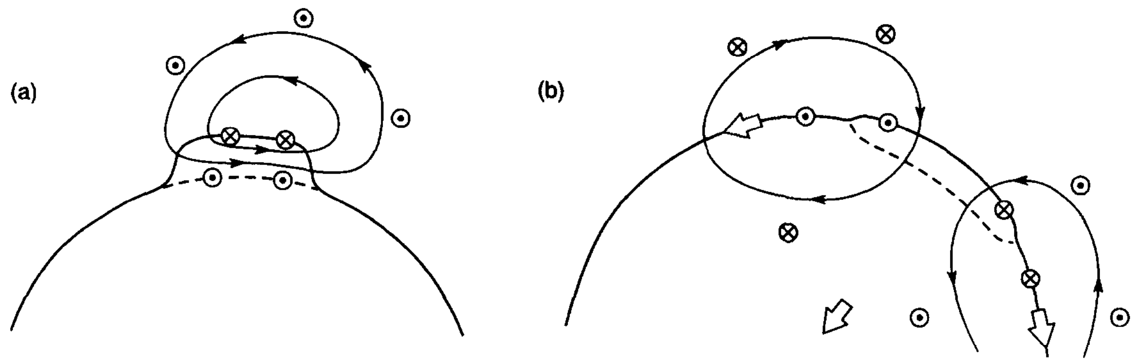

Fig.3. Northern hemisphere ionospheric flows for a pulse of dayside reconnection in the presence of positive IMF B_y illustrating the two-phase motion involved (from /26/).

mainly azimuthally in the ionosphere in a sense dependent on B_y, to the west in the northern hemisphere for B_y positive (as shown) and to the east for B_y negative (and vice versa in the southern hemisphere). At this time there will therefore exist a jet of azimuthal flow in the region of new open flux which will be closed in the incompressible ionosphere mainly at lower latitudes, because during this phase it is mainly the adjacent closed tubes which will be perturbed by its motion. (For strictly southward fields weaker azimuthal flows will occur during the corresponding initial interval, including "stretching" in azimuth, due to local time-dependent magnetosheath flow, with little poleward motion; this was not mentioned in the basic discussion given above.) However, after the distended open tubes have contracted over the dayside magnetopause the magnetosheath flow will begin to dominate their evolution into the tail, and the corresponding assimilation of the patch of new open flux into the polar cap, as shown in sketch (b). The precipitating plasma (and resultant auroral) characteristics would consist of an east-west (B_y-dependent) propagating patch of magnetosheath-like plasma which is formed in a region just equatorward of the polar cap (phase (a)), followed by poleward motion and decay (phase (b)). The source of magnetosheath plasma for the cusp ionosphere is "switched off" as the open tubes enter the tail; magnetosheath plasma still has access along the open tubes but then mainly flows away from the Earth in the plasma mantle rather than down to the cusp ionosphere as in the initial phase /17/. This behaviour of the cusp aurorae is strongly reminiscent of the properties of "midday auroral breakup events" observed by Sandholt and co-workers /18, 19/.

For reasons of clarity and simplicity we have so far discussed the effect of one pulse of dayside reconnection alone. It should be recognized, however, that there will generally be more than one "active" FTE present at any time at different stages of their evolution. This follows from the fact that the evolution of the flow and precipitation prior to assimilation into the polar cap takes place on a time scale of 10-15 min, while large FTEs are typically generated on a time scale of about half this /20/. For this reason the cusp precipitation and flow will be structured but essentially continuous. The bursty nature of the reconnection will be manifest, in particular, by "steps" in the dispersion profile of the cusp ion precipitation /17, 21/.

NIGHTSIDE IMPULSE RESPONSE

The basic ideas discussed above can also be applied to the nightside, as sketched in Fig. 4 (same format as Fig. 2). Here the destruction of open flux dF in the tail leads to the contraction of the region of open field lines via the excitation of twin-vortical flow which is initiated in the midnight sector. Now although the

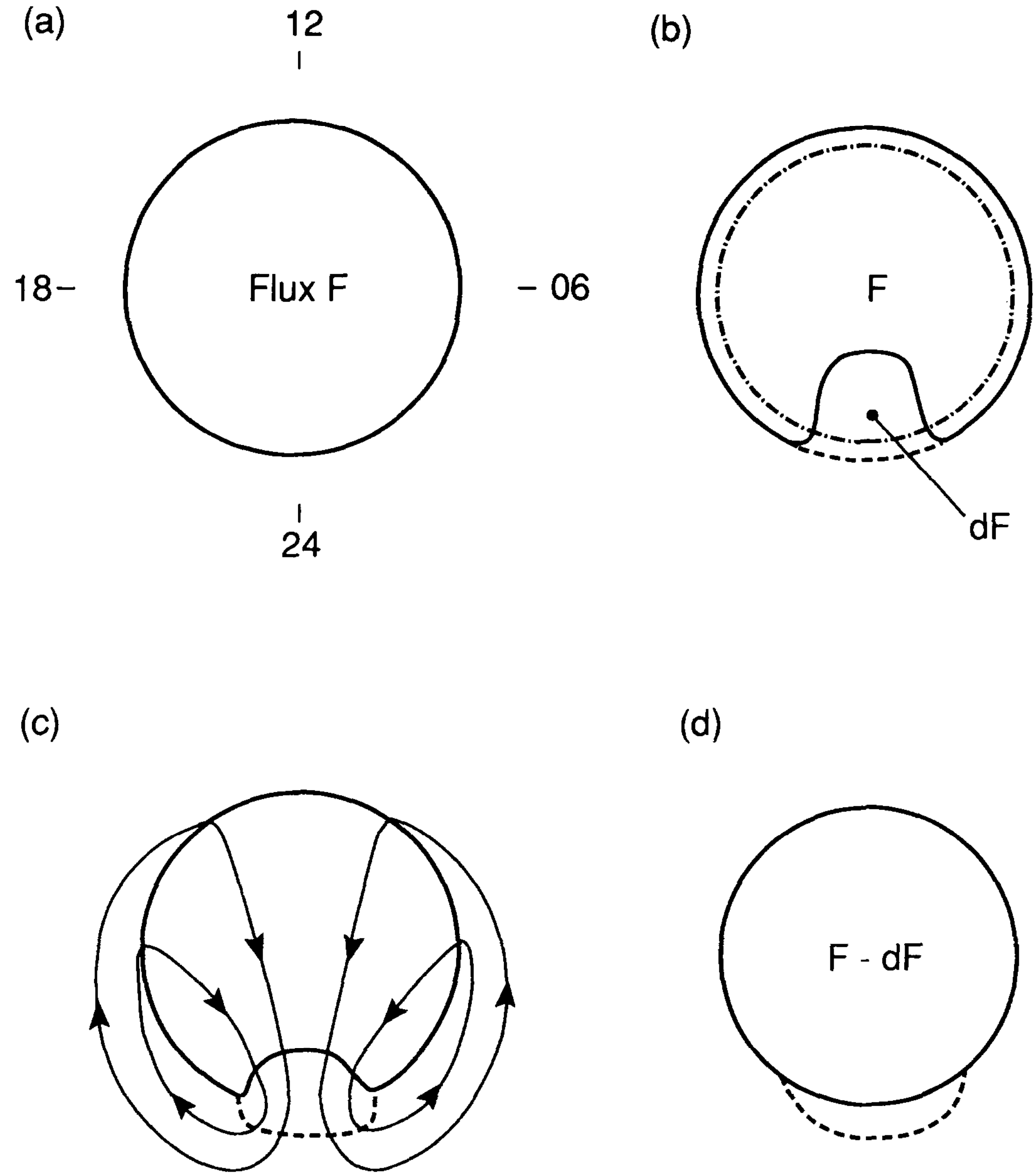

Fig.4. As for Fig. 2 except for a pulse of tail reconnection.

impulse response considered here simply represents a convenient theoretical starting-point which may be generalized to more continuous conditions (next section), radar studies of nightside flows show them to be characteristically pulsed in nature, at least some of this behaviour being related to the internal structure of substorms (i.e. to "multiple onsets") /22/.

The results of a recent study of nightside currents and flows during a multiple-onset substorm is summarized in Fig. 5 /23/. Here we show the evolution of the flows (speeds given in km s^{-1}) and current-carrying regions (dotted) at 2-min intervals during one excitation of the substorm; during the period studied such excitations occurred every ~ 12.5 min over a ~ 2-h interval. Sketch (a) shows the pre-excitation configuration, with the pre-existing (post-onset) quasi-steady westward electrojet lying equatorward of a low-current region. Since the flow speeds are similar in the two regions the implication is that the boundary represents a strong conductivity (and precipitation) gradient, with a Hall conductivity of ~ 20 mho in the electrojet and less than ~ 2 mho in the poleward region. At the onset of the excitation shown in sketch (b) a new intense current filament appears just poleward of the existing current, accompanied by the onset of a Pi2. The filament is deduced to have dimensions of ~ 200 km in latitude and ~ 500 km in local time, and initially expands poleward against the equatorward flow, and to the west, with phase speeds indicated in the broad arrows (again in km s^{-1}). Within the filament the flow speeds are observed first to be suppressed to very low values (< 100 m s^{-1}) for 2-4 min, implying that the conductivity of the region must be very large indeed, of order ~ 100 mho or more. After ~ 4 min an equatorward motion of the filament becomes discernable even though the flow within it remains small (sketch (c)), and then after ~ 5 min a large flow surge develops within the region, with equatorward speeds of up to ~ 1 km s^{-1}. At this time the filament moves more rapidly equatorward to coalesce with the pre-existing current (sketch (d)), such that after ~ 8 min the flows and currents become relatively steady once more, though generally leaving the lower-latitude electrojet either expanded in latitude or enhanced in magnitude, or both. It is inferred that the sudden flow surge takes place as the conductivity within the new current region declines, since there is no marked change in the magnetic disturbance at that time.

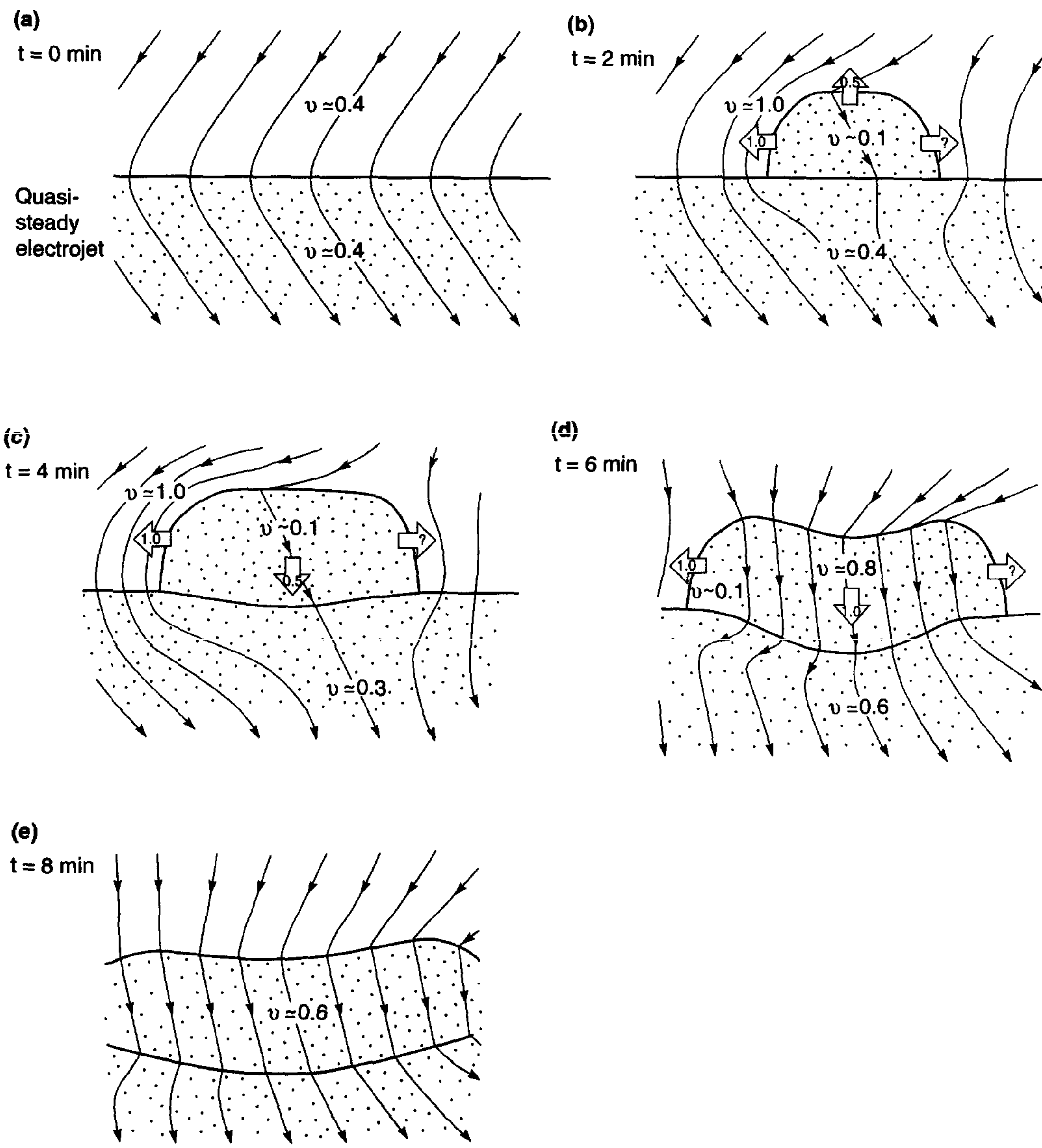

Fig.5. Evolution of current-carrying regions (dotted) and flows during an excitation of a multiple-onset substorm (from /23/).

Comparison of this behaviour with the reconnection-driven impulse response in Fig. 4 shows considerable similarities, though it appears clear that the flows are additionally modulated by strong ionospheric conductivity constrasts and that the coalescence of the current-carrying regions involves more than a simple convection of the new current-carrying region with the equatorward plasma flow (i.e. the structure also propagates across field lines, wave-like, in the plasma rest frame). Nevertheless, it appears plausible to associate such substorm excitations with bursts of reconnection in the geomagnetic tail, with the basic interpretation shown in Fig. 4. However, such a reconnection-driven interpretation requires that the pre-existing boundary between the electrojet and the low-current region on its poleward side represents the boundary between open and closed flux, and at present we have no unambiguous knowledge that this is actually the case. We must recognize that essentially any current disruption process which causes dipolarization of tail-like field lines could produce such an effect. The consequences could still be descibed in terms of Fig. 4, but now expressed e.g. in terms of an equilibrium configuration of tail-like plasma sheet and quasi-dipolar ring-current flux tubes which is perturbed by a dipolarization event. Combined space- and ground-based observations are required to firmly establish the physical processes responsible for these time-dependent effects.

CONTINUOUS RECONNECTION AND THE STEADY STATE

The impulse response of the system has been discussed extensively above because it represents an appropriate theoretical starting-point and because it has important geophysical applications to FTEs and to the multiple onsets of substorms. The concepts introduced, however, are not restricted to the description of the effect of impulses, but are equally applicable under more continuous conditions, including the limiting case of the steady state.

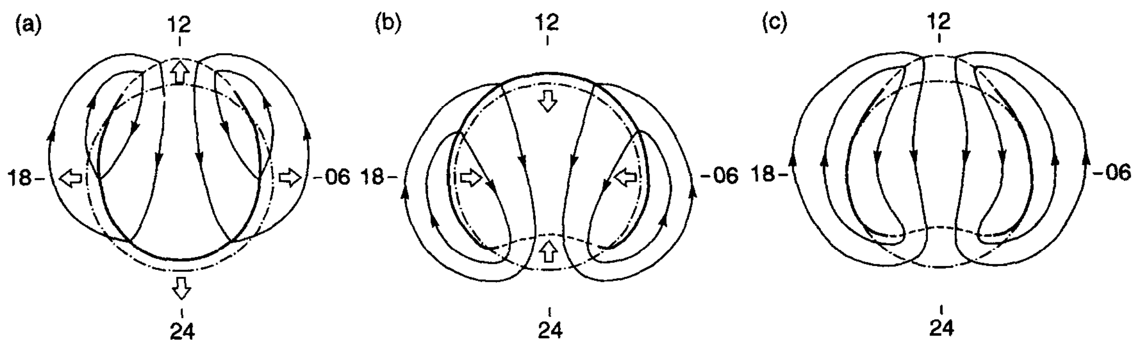

Fig.6. Ionospheric flows for (a) steady unbalanced dayside reconnection (the Siscoe-Huang problem), (b) steady unbalanced nightside reconnection, and (c) steady balanced reconnection (after /10/).

Our interpretation of conditions during steady unbalanced dayside and nightside reconnection are shown in Fig. 6. Here the boundary between open and closed flux is shown by the dashed and solid lines, where the dashed line corresponds to the "merging gap" which maps to the reconnection region where the flow crosses the boundary in the boundary's rest frame, and the solid line corresponds to the "adiaroic" portion of the boundary which moves exactly with the flow. The simultaneous position of the equilibrium boundary containing the same amount of open flux is indicated by the dot-dash line and is again shown conventionally circular. In the case of continuous unbalanced dayside reconnection (sketch (a)), the open-closed boundary lies equatorward of the equilibrium boundary in the vicinity of the noon-sector "merging gap" and poleward of it elsewhere, and both expand outwards as the open flux accumulates in the system. The flows are again of twin-vortical form and stronger on the dayside than the nightside; an analytic model of the flow in this case has been derived by Siscoe and Huang on the simplifying basis that the open-closed field line boundary remains circular as it expands /24/. (The flow in the tail lobe will exhibit a similar form as the lobe flux is increasingly compressed by the addition of open tubes on the outside while none are removed by tail reconnection adjacent to the plasma sheet on the inside.) The displacement between the actual open-closed field line boundary and the equilibrium boundary represents the potential which is in the system for flow. If dayside reconnection were to be switched off at any instant the boundaries would immediately stop growing and the actual boundary would move towards and coalesce with the equilibrium boundary on the ~ 10-15 min time scale, after which the flow would stop (the ionospheric and interplanetary electric fields then being totally inductively decoupled as described above).

Similarly, for steady unbalanced tail reconnection (sketch (b)), the open-closed field line boundary is displaced poleward of the equilibrium boundary in the vicinity of the midnight-sector "merging gap" and equatorward of it elsewhere, and both contract polewards as the open flux in the system diminishes. The twin vortical flows are now stronger on the nightside than on the dayside, corresponding to decreasing compression of the tail lobe field as open flux is removed by tail reconnection adjacent to the plasma sheet while none is added to its outer surface by dayside reconnection. Again, if the tail reconnection were to be switched off the system would approach equilbrium on ~ 10-15 min time scales and the flow would decay to zero.

If, however, we instead start up dayside reconnection at the same rate as the tail reconnection then a steady flow will be approached after a ~ 10-15 min interval (though the tail will not be steady-state through its whole length), with the open-closed field line boundary displaced equatorward of the equilibrium boundary at noon and poleward of it at midnight (sketch (c)). This flow is essentially the sum of the flows shown in sketches (a) and (b), and hence is larger than the latter, particularly on the nightside in case (a) and on the dayside in case (b). If we consider the voltage across the central polar cap (i.e. approximately across the dawn-dusk meridian), for example, then in cases (a) and (b) this will be just half the unbalanced reconnection voltage, which will add together to give the full reconnection voltage in the steady state case (c) /25/. The fact that the near-Earth system can transform from one of these flow patterns to another on a time scale of 10-15 min (depending on reconnection activity at the dayside and in the tail), a time scale very much shorter than the overall cycle time of the vortical flow on which the geometry of a given open flux tube evolves as it moves through the tail (typically several hours), is again a manifestation of the general inductive decoupling between ionospheric and interplanetary electric fields, though not in such an extreme form as occurs when all reconnection is switched off and the near-Earth flow dies to zero.

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