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INCOHERENT SCATTER RADAR OBSERVATIONS RELATED TO MAGNETOSPHERIC DYNAMICS

S. W. H. Cowley* and M. Lockwood**

Department of Physics and Astronomy, University of Leicester, University Road, Leicester LE1 7RH, U.K.
***Rutherford Appleton Laboratory, Chilton, Didcot OX11 0QX, U.K.*

ABSTRACT

Over the past decade incoherent scatter radars have provided fundamental observations of velocities and plasma parameters in the high-latitude ionosphere which relate to the dynamical processes responsible for the excitation of flow in the coupled solar wind-magnetosphere-ionosphere system. These observations have played a central role in inspiring a change of paradigm from a picture of quasi-steady flows parameterised by the direction of the interplanetary magnetic field to a picture of inherently time-dependent flows driven by coupling processes at the magnetopause and in the tail. Flows and particle precipitation in the dayside ionosphere are reasonably well understood in principle in terms of the effects of time-dependent reconnection at the magnetopause, though coordinated high- and low-altitude observations are lacking. Related phenomena also appear to occur in the tail, forming the "equatorward-drifting arcs" which are present during quiet times, as well as during the growth and early expansion phases of substorms. At expansion onset, the substorm bulge forms well equatorward of the arc formation region, and may take ~10 min or more to reach it in its poleward expansion. Nightside ionospheric flows are then considerably perturbed by the effects of strong precipitation-induced conductivity gradients.

INTRODUCTION

The first major sources of information about convection in the coupled magnetosphere-ionosphere system were obtained during the 1970s and early 1980s from observations of the ionospheric plasma flow and associated electric field by low altitude polar-orbiting spacecraft. These provided observations of the flow along the spacecraft track on ~15 min passes over the polar regions, every ~90 min for a given hemisphere. By combining data obtained from various local times under similar geophysical conditions, overall flow patterns were discerned and related to concurrent magnetospheric processes [e.g. Reiff and Burch (1985), and references therein]. The principal result of these studies was that the high-latitude flow responds strongly to the direction of the interplanetary magnetic field (IMF), thus immediately showing that magnetic reconnection is a principal magnetopause coupling process, as originally envisaged by Dungey (1961). It was found that when the IMF points south (i.e. B_z is negative) a twin-vortex flow is present, whose size and strength (as measured e.g. by the area of the polar cap and the voltage across it) both increase as the southward field increases. Dawn-dusk flow asymmetries are also present, opposite in opposite hemispheres, which are related to IMF B_y. As IMF B_z becomes small and turns northward, however, the flow system is typically contracted in size, the twin-vortex flows die away, and B_y-dependent lobe circulation cells appear within the polar cap, which are believed to be driven by reconnection between the IMF and open lobe field lines. These important results were summarized in the form of a sequence of steady-state flow patterns parameterised by the direction and strength of the IMF.

Although such "quasi-steady" pictures of the ionospheric flow represented a great step forward in knowledge of convection and encapsulated substantial relevant physics, they are nevertheless incomplete in a number of respects. First, a characteristic feature of the IMF is its variability over a wide range of time scales, particularly the critical north-south component. While we may envisage the flow evolving through quasi-steady states if the IMF varies sufficiently slowly in time at the magnetopause, very often the IMF varies rapidly in direction, for example across tangential discontinuities convecting in the solar wind. How the flow then responds to such changes is clearly not described by such pictures. Second, it has been found that even for steady interplanetary conditions, magnetopause coupling can be pulsed in "flux transfer events" (FTEs) which recur on 5-10 minute time scales (Haerendel *et al.*, 1978; Russell and Elphic, 1979). This should lead to pulsed flow in the magnetosphere-ionosphere system which again is not described by the "quasi-steady" patterns. Third, in describing the flow by quasi-steady patterns in a reconnection scenario one is in effect assuming that the dayside and nightside reconnection rates are nearly in balance with each other. However, this cannot in principle be correct because the tail reconnection site typically lies 100 R_E downstream from the dayside magnetopause (at least during quiet times), implying a relative propagation and response delay to changes in the IMF of at least 30 minutes. Inevitably, therefore, intervals of this order of unbalanced dayside and nightside reconnection will occur, involving increases and decreases in the amounts of open flux in the system. In other words, such quasi-steady pictures parameterised by the IMF do not allow for a necessary independent role of reconnection in the geomagnetic tail, and as a consequence are also incapable of encapsulating the variations of the flow system which occur during the substorm cycle. It is in these three areas that incoherent scatter radars have provided fundamentally important observations over the past decade, as will be described in the following sections.

FLOW RESPONSE TO CHANGES IN THE Z COMPONENT OF THE IMF

The first incoherent scatter observations to have the temporal resolution and spatial coverage needed to provide detailed information about the response of the twin-cell flow to changes in IMF B_Z were obtained in 1984/85 using the EISCAT UHF "Polar" experiment. The radar beam was pointed at low (21.5°) elevation to the north of the transmitter site at Tromsø, and cycled between two pointing directions 12° on either side of the L-shell meridian, with a cycle time of 5 min. F-region data were obtained at magnetic latitudes above ~71°, with the highest latitude being determined by the topside electron density. Figure 1 shows two examples from Todd *et al.* (1988), where 15 s line-of-sight velocities are shown with positive values indicating flow away from the radar. The squares and triangles are from the "west" and "east" radar azimuths, respectively, such that the "square wave" seen in the data results from the swinging of the radar beam during the experiment cycle. Positive values in the "west" azimuth and negative values in the "east" azimuth are indicative of predominantly westward flow in the equatorward part of the dusk convection cell, which grows as the amplitude of the "square wave" increases. Also plotted in these figures are IMF B_Z data obtained by the AMPTE-IRM spacecraft, which have been time-shifted to account for the estimated propagation delay from the spacecraft to the subsolar magnetopause. The left-hand panel, obtained at ~17:30 MLT, shows a westward flow onset across the field-of-view of the radar at ~15:02 UT, which occurred in response to a southward turn of the IMF at the magnetopause at ~14:51 UT. The response delay was thus ~11 min. Analysis of the beam-swung vectors in the lowest latitude gate, for example, indicate an increase in the westward flow from ~290 m s^{-1} at 14:55 UT to 940 m s^{-1} at 15:10 UT. The right-hand panel, obtained at ~15 MLT, shows a reduction in north-westward flow across the field-of-view starting near 12:22 UT, which occurred in response to a northward turning of the IMF at the magnetopause at ~12:19 UT. The flow response delay in this case was thus ~3 min. The flow then decayed to smaller values on a time scale of ~15 min, the speed in the lowest gate falling from 1190 m s^{-1} at ~12:15 UT to 560 m s^{-1} at ~12:33 UT. The increase in line-of-sight flow speed observed towards the end of the interval was temporary, and appears to have been due to an impulsive magnetopause phenomenon whose duration was smaller than the 5 min cycle time of the experiment.

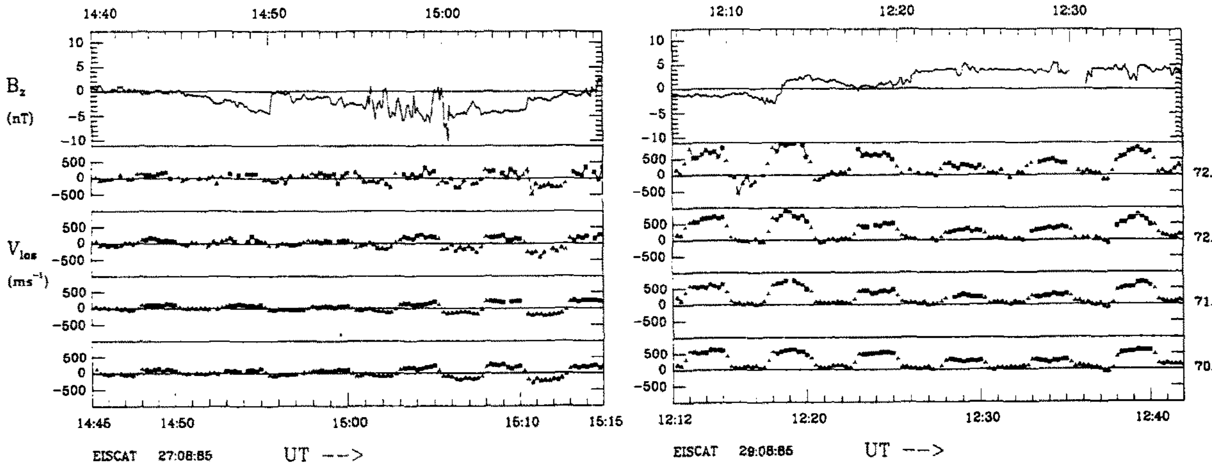

Fig. 1. EISCAT "Polar" flow data and AMPTE-IRM IMF B_Z data, showing the flow response to a southward (left) and northward (right) turn of the IMF. From Todd *et al.* (1988).

The left-hand panel of Figure 2 provides a summary of the results obtained from the EISCAT/AMPTE experiments, where the triangles and squares show the response delay to northward and southward IMF turnings, respectively, obtained by Todd *et al.* (1988), while the dotted line shows the results of a cross-correlation analysis using the same data set by Etemadi *et al.* (1988). Minimum response delays of ~5 min were obtained near noon, increasing to ~10-15 min near dawn and dusk. These results imply that flow is excited first near noon within a minute or two of Alfvénic information arriving along the field lines from the magnetopause (itself taking ~2 min), then spreads out in local time with a phase speed of ~5 km s^{-1}. A phase speed of 2.6 km s^{-1} was measured directly from ion temperature enhancements (due to enhanced ion-neutral frictional heating) in the beam-swung data in one example at ~14:00 MLT (Lockwood *et al.*, 1986), while 6 km s^{-1} was similarly determined at ~13:00 MLT in a later experiment to be discussed further below (data shown in Figure 4). The right-hand panel of Figure 2 shows response delay results from subsequent studies. The solid symbols show the response to a southward turning across the nightside hours, determined from data from the Millstone Hill (MHR), Sondrestrom (SOND), Wick and EISCAT radars (Lester *et al.*, 1993). Similar results to those of Todd *et al.* (1988) were obtained near dusk (response times of ~10-15 min), increasing to ~40 min at the Wick radar at midnight. However, the latter value may be increased somewhat by the relatively low latitude of the Wick field-of-view, 59°-66°, probably requiring the flow system to expand before the onset of backscatter was observed. The results from EISCAT in the post-midnight sector were unfortunately inconclusive in this instance, due to the 30-min cycle time of the CP-3 experiment which was being run at that time. The data shown by the open symbols in this panel were obtained in the study by Taylor *et al.* (1994), and show low response times throughout the nightside hours. However, the southward turn in this case was also accompanied by an interplanetary shock, which will produce its own rapid flow effects.

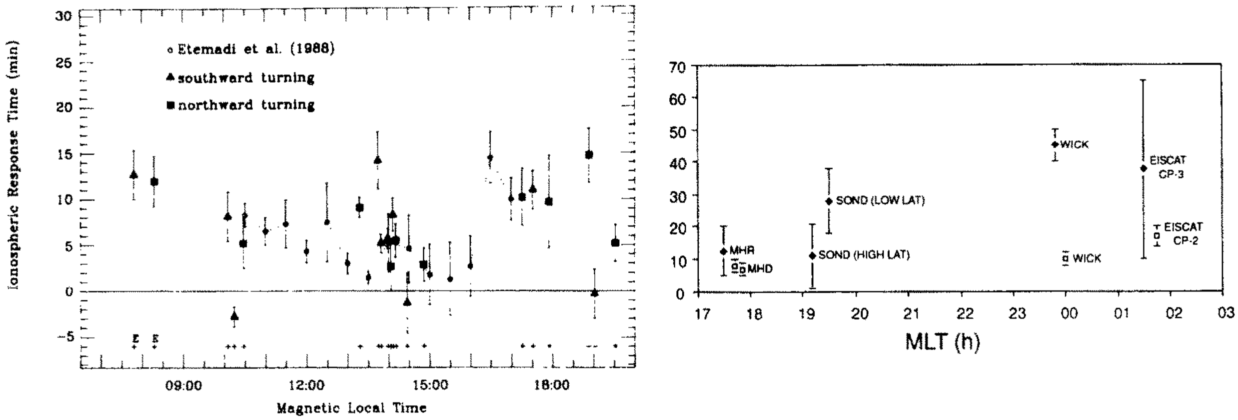

Fig. 2. Ionospheric flow response time (in minutes) to changes in the north-south component of the IMF, versus magnetic local time. Left panel from Todd *et al.* (1988), right panel from Taylor *et al.* (1994).

The picture of the flow response proposed by Cowley and Lockwood (1992) on the basis of these results is illustrated in Figure 3, which combines together ideas on boundary motions and flows discussed previously by Siscoe and Huang (1985) and Freeman and Southwood (1988). The basic idea behind this picture is that if all magnetopause coupling is switched off, together with reconnection in the tail, then the near-Earth system will approach equilibrium and the flows will die away, even if open flux is still present. Subsequent reconnection at the magnetopause or in the tail perturbs the system away from this equilibrium, and excites flow which carries the

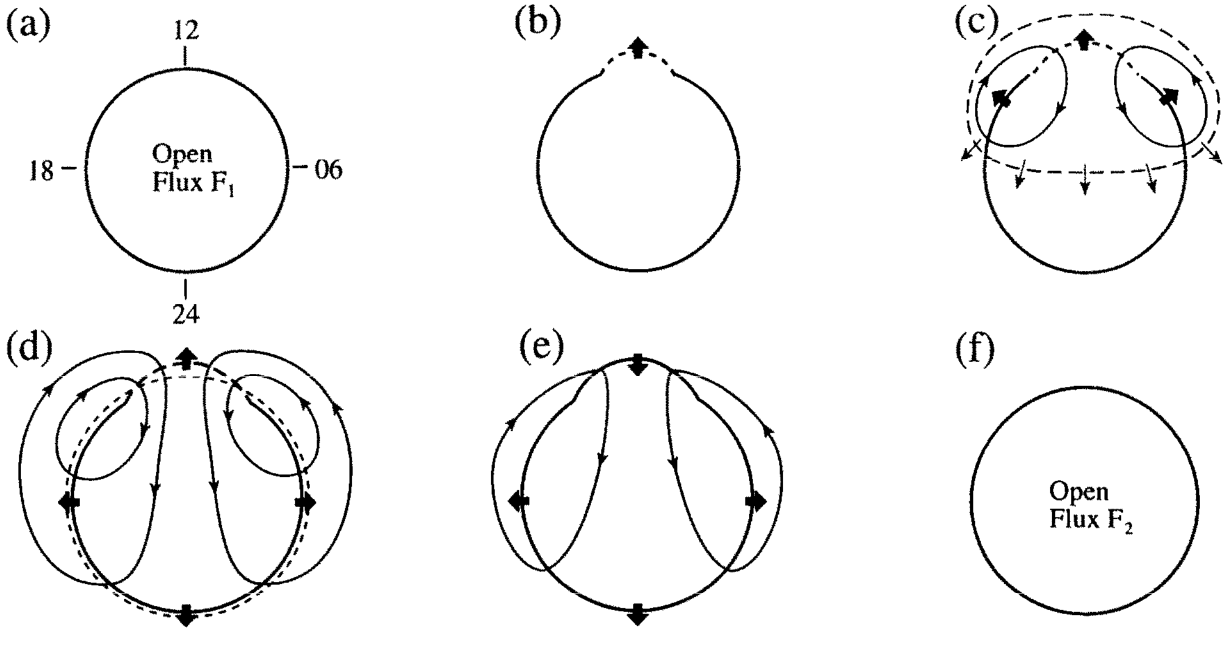

Fig. 3. Sketches illustrating the ionospheric flow response to a southward followed by a northward turn of the IMF. Only the effect of open flux tube production at the dayside magnetopause is depicted. After Cowley and Lockwood (1992).

system towards a new equilibrium with the changed amount of open flux. Figure 3 shows how this applies to the onset and cessation of open flux production at the dayside magnetopause, produced e.g. by a southward followed by a northward turning of the IMF. For simplicity we do not include the effects of lobe or tail reconnection in this discussion, so as to isolate the effects of the magnetopause reconnection rate variations. The figure shows views of the northern polar ionosphere, and in (a) we suppose that the IMF has been northward for a significant interval such that there has been no dayside reconnection and the near-Earth flow has died away as the system approaches equilibrium, even though open flux F_1 is present. The IMF then turns south at the subsolar magnetopause, and dayside reconnection starts. The first thing to happen is that the open-closed field line boundary moves equatorward in the noon sector, representing departure from equilibrium, as shown in (b), followed by the excitation of flow, (c), which appears first near noon and expands over the polar cap at a phase speed of several km s^{-1}. After 15-20 min the flow has expanded to cover the whole of the polar region, (d), and is accompanied by an expanding open-closed field line boundary at all local times. This corresponds to the situation analysed by Siscoe and Huang (1985). The dashed-line portion of the open-closed boundary maps to the dayside reconnection region; the plasma crosses this boundary as the field lines become open. At the solid-line segments the boundary moves exactly with the plasma flow. The 15-20 min time scale for full flow excitation represents the time scale for open tubes to move from the dayside reconnection sites into the near-Earth tail, and for the near-Earth system to respond to these flux changes at Alfvénic propagation speeds. The lighter dashed line in (d) shows the equilibrium position of the open-closed boundary which would contain the same amount of open flux F_2. If the IMF now turns northward once more and dayside reconnection ceases, then declining twin-vortical flow will be maintained until the open-closed boundary approaches the equilibrium position over an interval of ~20 min, as shown in (e). After this, however, the flows will have died away to small values, as shown in (f), and will so remain until further reconnection occurs either at the magnetopause or in the tail.

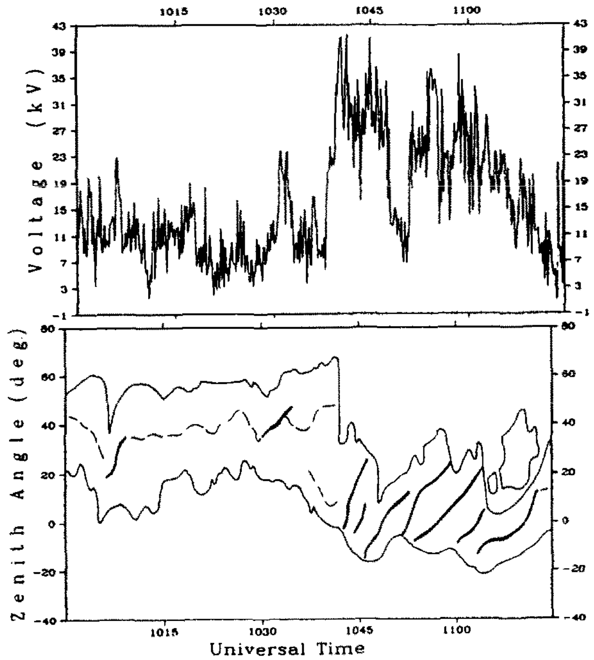

Fig. 4. EISCAT CONV flow data (top) and MSP observations of 630 nm cusp emission (bottom) obtained on 7 January 1992. From Lockwood *et al.* (1993b).

An example of correlated boundary motion and flow excitation is shown in Figure 4, taken from Lockwood *et al.* (1993b). The lower panel shows the position of the 630 nm cusp emission obtained by a meridian scanning photometer (MSP) located at Ny Ålesund, Svalbard, plotted versus zenith angle, where positive angles are to the north. The solid lines show the borders of the emission, the dashed lines the relatively stable peaks, and the heavy lines the poleward-moving peaks of dayside "auroral breakup" events (to be discussed further in the next section). The upper panel shows the voltage across the equatorward portion of the dusk (~13:00 MLT) convection cell, derived from flows measured by the EISCAT CONV experiment in the region immediately equatorward of the cusp aurora (this panel has been displaced by 110 s relative to the lower one to account for the mean lifetime of the excited oxygen which gives rise to the 630 nm emission). The radar experiment used two poleward-pointing beams like the "Polar" experiment, but now transmitted simultaneously by the UHF and VHF radars. Flow vectors were derived with 10 s resolution over the latitude range 71°-76°, and the voltage determined by integrating the westward velocity component over this range. It can be seen that, in conformity with the picture presented in Figure 3, the cusp auroras started to move equatorward at ~10:35 UT and that shortly thereafter a large increase in the flow voltage took place, from 5 to 40 kV.

FLOW RESPONSE TO PULSED DAYSIDE RECONNECTION

As indicated above, it has been known since the *in situ* measurements by the HEOS-2 and ISEE-1/-2 spacecraft in the 1970s that the reconnection which occurs at the dayside magnetopause for southward-directed IMFs is characteristically pulsed on time scales of 5-10 min, giving rise to "FTE" signatures. It has also been found that under these conditions the cusp auroras and flows are similarly pulsed in dayside "auroral breakup" events (Lockwood *et al.*, 1989; Sandholt *et al.*, 1990). An example is shown on the right-hand sides of the panels in Figure 4, where correlated auroral and flow transients occurred after the auroras moved equatorward. We infer that a southward turn of the IMF took place at that time, though this cannot be confirmed in this case because the IMP-8 spacecraft was not tracked at that time. Further examples from later on the same day are shown in Figure 5, taken from Moen *et al.* (1995). Here from left to right we show 630 nm MSP scans versus zenith angle, the integrated 557.7 nm intensity (taken to be an indicator of region 1 current flow), the dusk cell voltage obtained from EISCAT

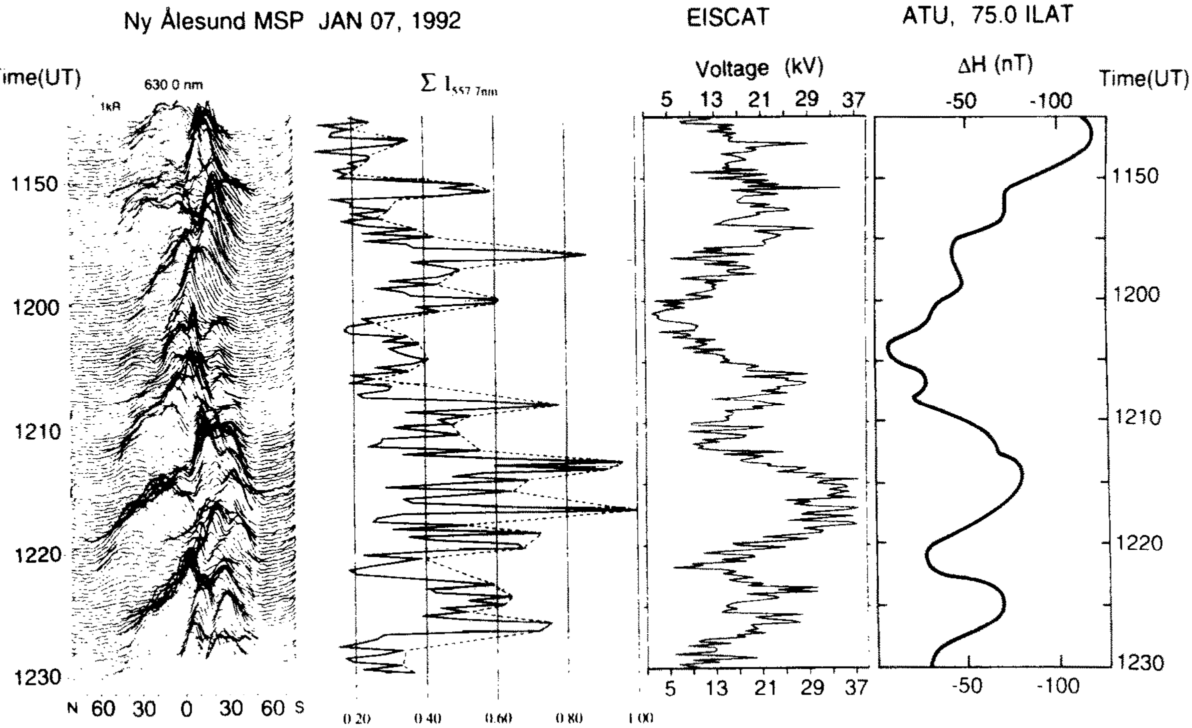

Fig. 5. MSP 630 nm cusp emission profiles, the integrated 557.7 nm emission, the dusk flow cell voltage determined from EISCAT CONV flow data, and the H component magnetic perturbation observed at Greenland West station ATU, on 7 January 1992. From Moen *et al.* (1995).

CONV data as above, and the H-component magnetic perturbation from Greenland West station ATU (at 75° magnetic latitude). The MSP/EISCAT data correspond to mid-afternoon local times, ~15:00 MLT, while ATU was in the mid-morning sector, at ~10:00 MLT. Six poleward-moving transients were observed in the interval shown in the MSP data. The first three were separated by intervals of ~5 min, and were associated with a single peak in the dusk cell voltage. The next three were separated by ~10 min, and gave rise to separated voltage peaks. Corresponding variations occurred in the H-component at ATU (and over much of the Greenland magnetometer chain), indicative of eastward flows in the equatorward part of the dawn cell, showing that the pulsing of the flow occurred across the whole dayside ionosphere and was not localized to the vicinity of the auroral transients in the afternoon.

The theoretical interpretation of these events is just the impulse version of that outlined above in relation to Figure 3, with IMF B_y field tension effects included. Each reconnection impulse excites flow for ~15-20 min, such that if the impulses recur on a comparable or longer time scale, individual flow pulses result, while if they recur on a shorter time scale the flow becomes essentially continuous, as seen in Figure 5. The issue of whether reconnection is more usually continuous or more usually pulsed is a matter of observation rather than of theory, but radar data from within the cusp itself seem characteristically to be pulsed in concert with the expected "steps" in the cusp ion dispersion profile observed in spacecraft overpass data (Cowley *et al.*, 1991; Lockwood *et al.*, 1993a).

A major gap in the observational chain, however, results from the present lack of coordinated observations at the magnetopause and in the ionosphere. Only one example of such simultaneous data has so far been published, obtained in 1986 using magnetic data from ISEE-2 and flow data from the EISCAT "Polar" experiment (Elphic *et al.*, 1990). These data are shown in Figure 6, where on the left we show magnetic data from ISEE-2 and from EISCAT, while on the right we show meridian scans of 630 nm cusp emission and 557.7 nm all-sky camera images represented as isophotic contours, both obtained at Ny Ålesund. A sequence of flow transients are seen in the EISCAT data, directed westward and poleward, which were coherent over all range gates. These were associated with westward- and poleward-moving auroral transients seen in the optical data, which were observed south of zenith at Ny Ålesund and within the poleward part of the EISCAT field-of-view. EISCAT thus directly observed the motion of newly-opened field lines associated with the transient auroras, the westward motion near noon resulting from the field tension effects of a positive IMF B_y observed by ISEE-2 (not shown). (Note that this situation is different to that shown in Figure 5 where the active auroras were located just poleward of the most poleward part of the EISCAT field-of-view, and the azimuthal motions were opposite, westward at EISCAT and eastward for the auroras. In this case, therefore, while the auroras were inferred to lie on newly-open field lines in the presence of negative IMF B_y, EISCAT observed westward flows on closed field lines at lower latitudes which

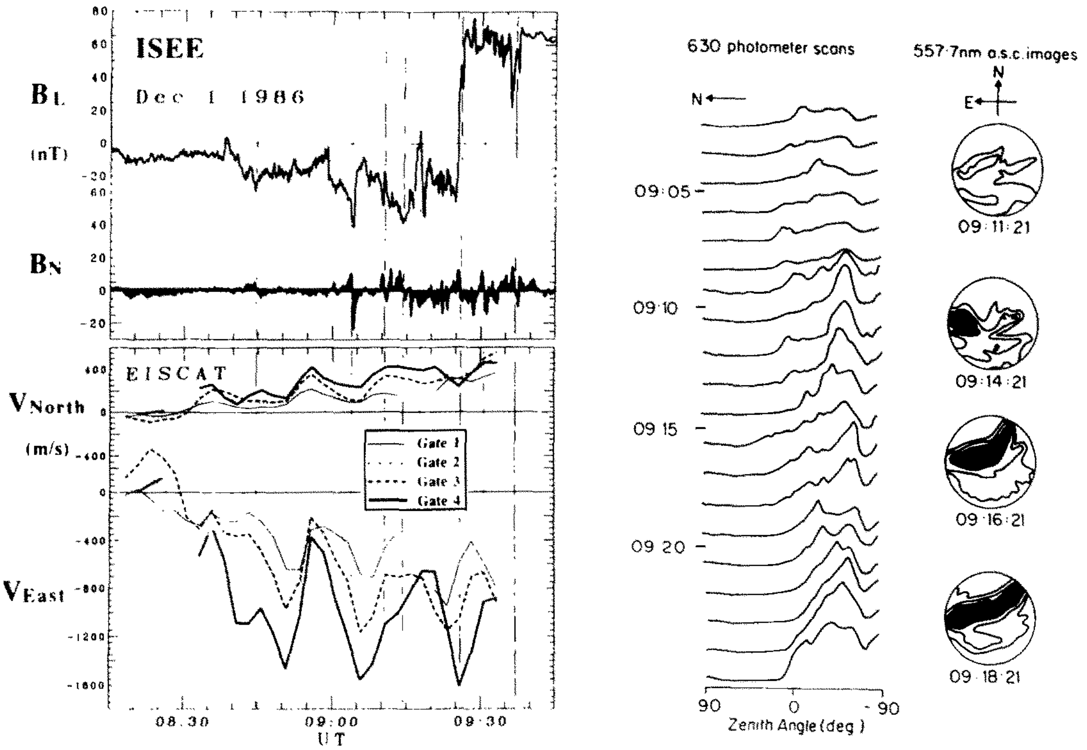

Fig. 6. ISEE-2 magnetic field data, EISCAT "Polar" flow data, 630 nm MSP data, and 557.7 nm all sky camera images obtained on 1 December 1986. From Elphic *et al.* (1986).

were excited by the transient magnetopause processes.) The ISEE-2 data shown in the upper panel on the left side of Figure 6 were obtained during an inbound pass at ~13:30 MLT and ~35° magnetic latitude. The spacecraft was initially located in the magnetosheath where the L-component (essentially the northward component tangential to the magnetopause) was negative, and passed across the magnetopause into the magnetosphere at ~09:30 UT. The N-component (normal to the magnetopause, positive out) then showed the presence of several bipolar "FTE" signatures, which together with the spikes in the L-component, are indicative of transient reconnection occurring at the magnetopause. These are marked by the vertical lines in the panel. It can be seen that the first two major FTE perturbations were related to the first two flow/auroral transients seen by EISCAT and at Ny Ålesund, and that there was substantial magnetic activity near the magnetopause during the third flow/auroral transient. At the least, these data provide an example in which dayside flow and auroral transients occurred simultaneously with FTEs at the magnetopause, but, as indicated above, due to the present lack of appropriate data, this represents the only example published to date.

NIGHTSIDE OBSERVATIONS RELATED TO TAIL DYNAMICS AND SUBSTORMS

While the behaviour of dayside flows seems to be reasonably well understood in terms of magnetopause reconnection processes, nightside behaviour is more complex and less well developed. Figure 7 shows the expected response to a pulse of tail reconnection (Cowley and Lockwood, 1992). Starting from a zero-flow equilibrium in (a), the open-closed field-line boundary is first displaced poleward near midnight in (b), followed by the excitation of twin-vortex flow in (c), which dies away to small values in (d) as a new equilibrium is approached. The time scale for excitation and decay of the flow is again ~10-20 min. It is important to note that the newly closed flux and heated plasma precipitation is formed at the poleward edge of the open-closed field line boundary, and propagates equatorward. This behaviour is therefore quite distinct from the known characteristics of substorm expansion phase onset, which starts well equatorward of the open-closed field line boundary and propagates poleward (e.g. Cogger and Elphinstone, 1992).

Nevertheless, events of this nature do occur, as observed in data from the Sondrestrom radar during a quiet (non-substorm) interval (de la Beaujardière *et al.*, 1994). Figure 8 shows meridional electron density profiles from four successive 3-min radar scans, together with the north-south component of the plasma velocity. In scan 1 E-region precipitation from an east-west aligned auroral arc is observed at position A (also observed by all-sky camera), in the presence of weak equatorward flow. Spacecraft overpass data show that this arc lay immediately equatorward of the open-closed field line boundary, as indicated by the presence of a velocity-dispersed ion signature (VDIS) on

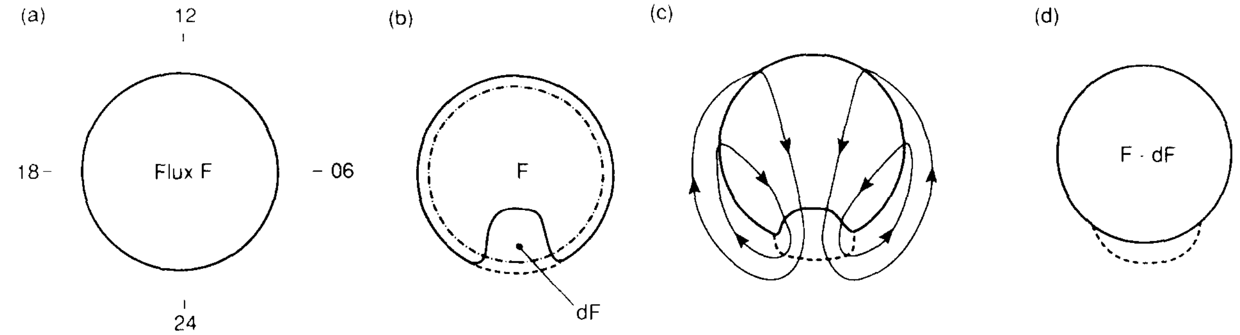

Fig. 7. Ionospheric flow and open-closed field line boundary response to an impulse of tail reconnection. From Cowley and Lockwood (1992)

its poleward side, which is believed to map to the outer boundary layer of the plasma sheet. In scan 2 this precipitation weakened, while in scan 3 it strengthened again in concert with the appearance of a new arc (B) on its poleward side, such that the precipitation boundary moved poleward by ~100 km. The equatorward flow simultaneously increased to ~300 m s^{-1}, though it was somewhat supressed within the high-density region of arc A itself. The poleward motion of the boundary in the presence of equatorward flow indicates the occurrence of a burst of tail reconnection, as discussed above. In scan 4 both arcs are present and move equatorward in the presence of a ~500 m s^{-1} flow. Subsequent data show that this flow died away to small values over a ~10 min interval. Examination of a 10-h interval of nightside data showed a 10-20 min recurrence interval for moderately-sized events, with major events like that shown in Figure 8 occurring about once per hour.

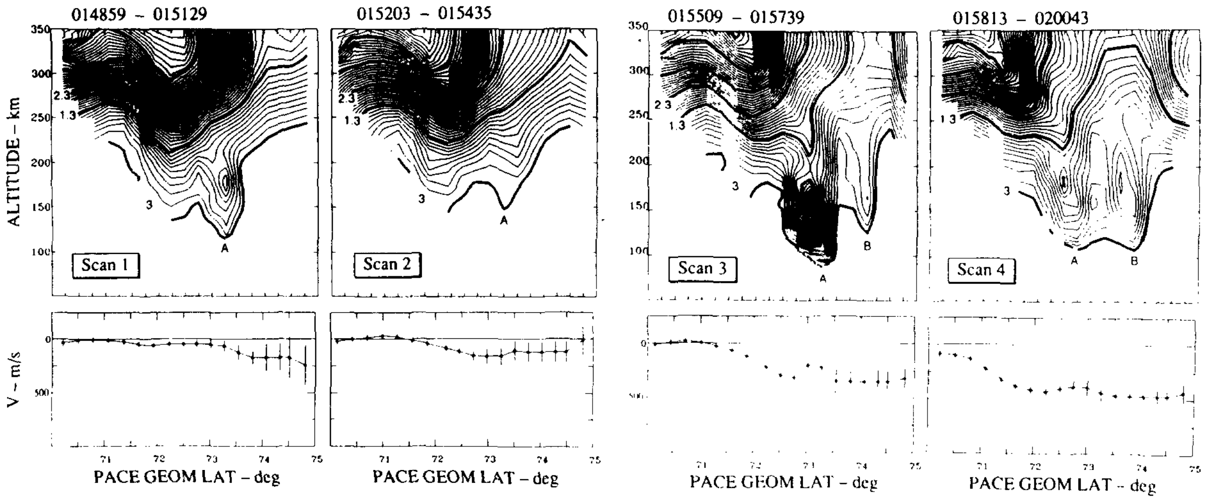

Fig. 8. Meridional electron density contour plots and northward velocities for successive 3-min scans of the Sondrestrom radar on 13 January 1989. From de la Beaujardière *et al.* (1994).

Related phenomena have also been observed by EISCAT, and in Figure 9 we show an example taken from Persson *et al.* (1994). Here the EISCAT UHF beam was pointed south of Tromsø at 40° elevation, and observed a sequence of electron temperature enhancements (indicative of soft electron precipitation) and topside electron density depletions (indicative of ion outflow). These moved steadily equatorward during a substorm growth phase at ~500 m s^{-1}, possibly mainly driven by dayside reconnection and an expanding polar cap. Expansion onset occurred at 21:11 UT well equatorward of Tromsø, as indicated by magnetic data from the IMAGE chain, which was followed by an electron temperature enhancement (soft electron precipitation) expanding poleward towards the radar. This is the image in the radar data of the expanding auroral bulge. An enhancement in the ion temperature, indicative of increased flows and ion-neutral frictional heating, was observed on its poleward border. Two important conclusions may be drawn. One is that substorm onset occurred well equatorward of the open-closed field line boundary i.e. well equatorward of where the growth phase equatorward-drifting arcs were formed. In another case study, Gazey *et al.* (1995) found that onset occurred at least 600 km equatorward of this boundary. The other is that a significant interval, ~10 min or more, elapsed before the bulge reached the latter boundary. Of course, we cannot in any simple way determine from the radar data the nature of the physical process which occurred in the tail which lead to the formation of the bulge, but if it was near-Earth reconnection and plasmoid formation, then we can say that the plasmoid was not pinched off until ~10 min or more after onset. During this

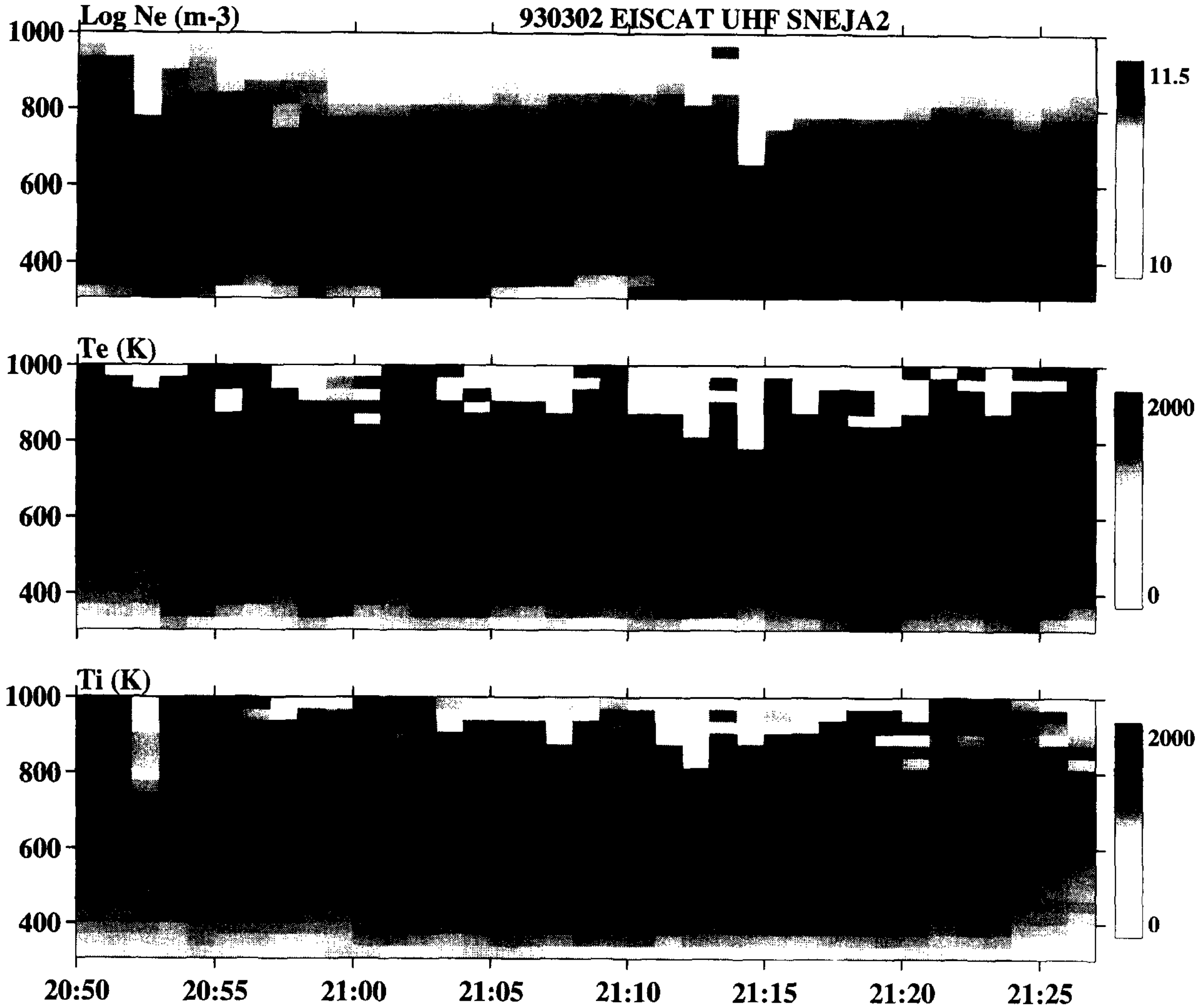

Fig. 9. EISCAT UHF measurements on 2 March 1993 of electron density, electron temperature and ion temperature versus range (km) on the vertical axes, and time (UT) on the horizontal axes, for a beam pointing south of Tromsø at 40° elevation. From Persson *et al.* (1994).

time the equatorward-drifting arcs continued to drift equatorward and into the poleward-expanding bulge, indicative of a completely separate dynamical phenomenon. As indicated above, the equatorward-moving arcs appear to originate in pulsed reconnection at a more distant tail site, though the equatorward motion may involve Earthward wave propagation as well as Earthward convection, since Gazey *et al.* (1995) have provided initial evidence that these arcs move equatorward faster than the plasma flow. Similar conclusions were also reached by Morelli *et al.* (1995) in the case of equatorward-moving electrojet filaments within the substorm-disturbed region, and these may prove to be a similar phenomenon related to the new nearer-Earth reconnection region.

An additional final complication in nightside studies is that flows are also modified by the extreme contrasts in E-region conductivity between nightside regions which have little precipitation (e.g. the nightside polar cap where the Hall and Pedersen conductivities may be ~1 mho or less), and regions where the precipitation is intense [e.g. the westward-travelling surge where the Hall conductivity may reach more than ~200 mho and the Pedersen conductivity more than ~50 mho, see e.g. Aikio and Kaila (1996)]. Radar data show that the flow is typically supressed to low values in the latter regions (while the intense precipitation lasts), so that the external flow is diverted around them, leading to perturbed directions and strong flows in the surrounding regions (Kirkwood *et al.*, 1988; Gazey *et al.*, 1995; Morelli *et al.*, 1995; Fox *et al.*, 1996). The latter flows are presumed to give rise to the enhanced ion temperatures observed at the poleward border of the expanding auroral bulge in the data shown in Figure 9. A sketch of the situation during the early phases of bulge formation is given in Figure 10, showing the open-closed field line boundary, the VDIS, the equatorward-drifting arcs, and the expanding auroral bulge, within which the flow is supressed and around which the external primarily equatorward flow is diverted.

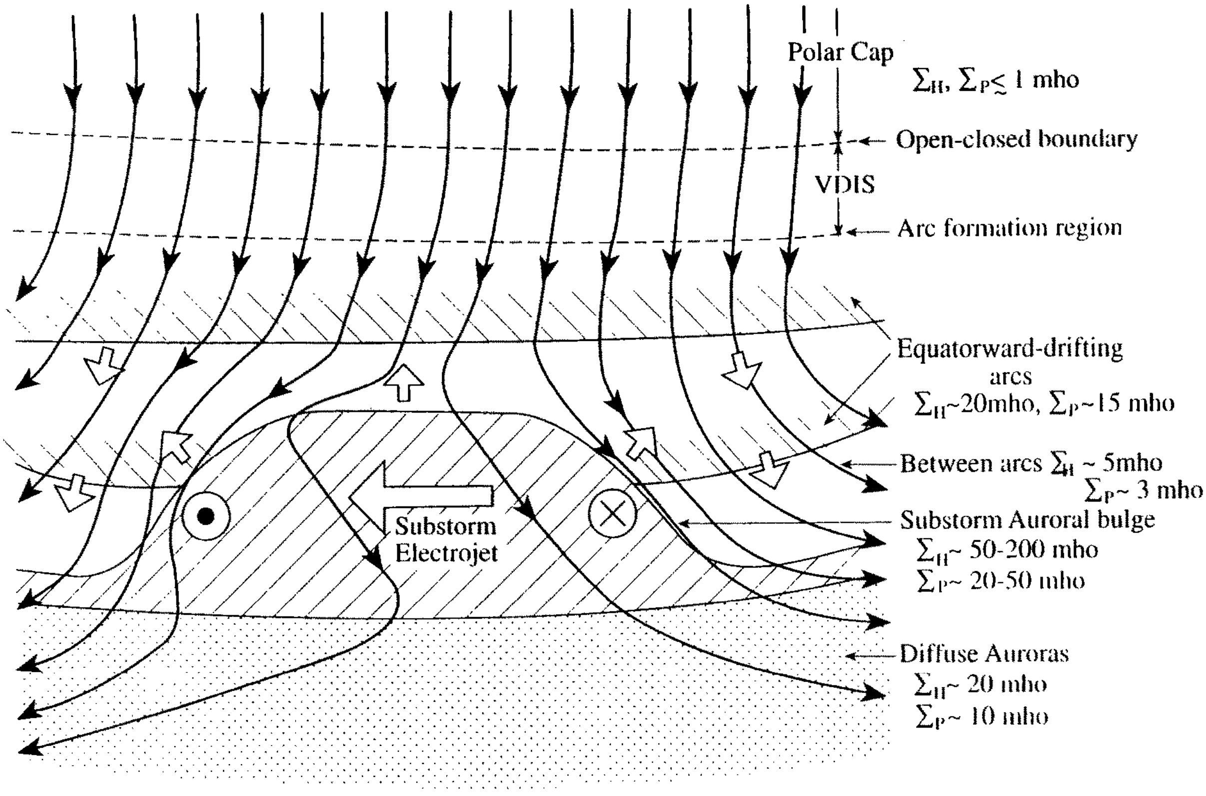

Fig. 10. Sketch of nightside flows, precipitation regions and resulting Hall and Pedersen conductivities early in substorm bulge formation.

SUMMARY

Incoherent scatter radar observations over the past decade have inspired a paradigm change in our picture of the flow in the coupled magnetosphere-ionosphere system, from quasi-steady patterns parameterised by the direction of the IMF, to intrinsically time-dependent flows driven separately by reconnection at the magnetopause and in the tail, which occur in the presence of increasing or decreasing amounts of open flux. Flows in the dayside ionosphere appear to be reasonably well understood in terms of time-dependent reconnection at the magnetopause, though there is a major gap in observational knowledge due to the lack of simultaneous space- and ground-based data. On the nightside, one class of disturbances, the equatorward-moving arcs which are present during quiet times and during the growth and early expansion phases of a substorm, appear to be similarly related to pulsed reconnection at a distant site in the tail. Onsets of the substorm expansion phase, however, are found to take place well equatorward of the open-closed field line boundary, and the bulge typically does not reach the latter for ~10 min or more. Nightside flows are further complicated by the effects of strong conductivity gradients, in which the flow is supressed in regions of high conductivity.

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