Magnetosphere-Ionosphere Interactions: A Tutorial Review

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We review the basic physics of the field-aligned current (FAC) systems which transmit energy and stress between the magnetosheath-magnetosphere system, and the ionosphere-thermosphere system. The specific topics covered include (a) ionospheric flow and currents, (b) the large-scale Region 1/2 current system associated with Dungey-cycle flow, (c) cusp currents and their relation to the interplanetary magnetic field; (d) travelling convection vortices, and (e) substorm-related current systems.

1. INTRODUCTION

The large-scale system of field-aligned currents (FACs) which transmit stress between the magnetosheath-magnetosphere, and ionosphere-thermosphere were first detected as "transverse magnetic disturbances" by the low-altitude polar-orbiting satellite 1963 38C (Zmuda *et al.*, 1966). They were not immediately recognised as the effect of FACs, however, and it was Cummings and Dessler (1967) who first suggested a link with the current system which had been proposed by Birkeland sixty years earlier (Birkeland, 1908; see also Dessler, 1984). A further ten years had to pass before the overall morphology of the FAC system became clear, as presented in a number of papers by Iijima and Potemra (1976 a, b; 1978), using triaxial magnetic data from the Triad satellite. The overall pattern consists of two contiguous rings of current, "Region 1" at higher latitudes and "Region 2" at lower latitudes, with opposite polarities at dawn and dusk and some overlap in the pre-midnight Harang region. A third system at higher latitudes than Region 1 on the dayside is associated with the dayside cusp (Iijima and Potemra, 1976b; Wilhjelm, *et al.*, 1978; Iijima *et al.*, 1978; McDiarmid *et al.*, 1978). This current pattern has been found to be an almost permanent feature of the magnetosphere-ionosphere system, though it is modulated in size, strength, and form both by the orientation and magnitude of the interplanetary magnetic field (IMF) and by geomagnetic disturbance. During relatively quiet times the total current flowing in the Region 1 system is ~1.6 MA, while that flowing in Region 2 is ~1.1 MA. During more disturbed times ($|AL|$>100 nT) the pattern expands typically by a few degrees, and the Region 1 and 2 currents increase to ~2.7 and ~2.5 MA respectively (Iijima and Potemra, 1978). Typical current intensities are ~0.5 to ~2 μA m^{-2}, again somewhat lower for Region 2 than for Region 1.

It is the principal purpose of this paper to discuss the physical origins of these currents, and some of their consequences. The central framework for our discussion will be Dungey's (1961) open model of the magnetosphere, in which plasma flow is generated principally by reconnection at the magnetopause between the terrestrial field and the IMF, and consequent related phenomena in the geomagnetic tail.

2. IONOSPHERIC FLOW, CONDUCTIVITY, AND CURRENTS

The flow imposed on the ionosphere by Dungey-cycle convection is shown schematically in Fig. 1, where the dashed line indicates the boundary between open and closed field lines. The flow consists of twin vortices, with

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antisunward flow over the polar cap, which maps to the magnetospheric tail lobes, and return sunward flow in the auroral zone, which maps mainly to the hot plasma sheet and ring current regions. When the ionosphere participates in such flow the plasma particles are subject to collisions with neutral atmospheric particles at lower altitudes in the E region, which causes a drag on the flow and heats the neutral gas. Assuming that the gas is stationary in the Earth's frame, an assumption which is usually valid as a first approximation, the force-balance equation for ions which determines the drift velocity $\boldsymbol{V}_i$ is

$$e(\boldsymbol{E}+\boldsymbol{V}_i \times \boldsymbol{B}) = m_i \nu_{in} \boldsymbol{V}_i \;, \qquad (1)$$

where $\boldsymbol{E}$ and $\boldsymbol{B}$ are the electric and magnetic fields, m_i the ion mass, and ν_{in} the ion-neutral collision frequency. The solution for the field-perpendicular flow is

$$\boldsymbol{V}_{i\perp} = \frac{1}{\left(1+\left(\frac{\nu_{in}}{\Omega_i}\right)^2\right)} \left[\frac{\boldsymbol{E}\times\boldsymbol{B}}{B^2} + \left(\frac{\nu_{in}}{\Omega_i}\right)\frac{\boldsymbol{E}}{B}\right] \;, \qquad (2)$$

where $\Omega_i = eB/m_i$ is the gyrofrequency. The first term is the $\boldsymbol{E}\times\boldsymbol{B}$ drift slowed by collisions, while the second describes mobility in the direction of $\boldsymbol{E}$ produced by them. It can be seen that the drift magnitude and direction depend on the ratio of the collision frequency to the gyrofrequency, though it is the former parameter by far which varies the most rapidly through the ionosphere, since the magnetic field strength is almost constant in the appropriate range of altitudes (~100-200 km). Because the neutral density increases rapidly with decreasing altitude, so does the ion-neutral collision frequency, with the condition $(\nu_{in}/\Omega_i) \approx 1$ being reached at an altitude of ~125 km (see the paper by Richmond, this volume, for further details). In the region somewhat above ~125 km, therefore, (ν_{in}/Ω_i) is small, such that the ion drift in the direction of $\boldsymbol{E}\times\boldsymbol{B}$ is not substantially diminished, while the ion mobility in the direction of $\boldsymbol{E}$ increases with decreasing height proportional to (ν_{in}/Ω_i). Similarly, in the region somewhat below ~125 km, (ν_{in}/Ω_i) becomes increasingly large compared with unity, such that the drift in the direction of $\boldsymbol{E}\times\boldsymbol{B}$ becomes negligible, and the ion drifts approximately in the direction of $\boldsymbol{E}$ with diminishing speed, inversely proportional to (ν_{in}/Ω_i). The ion mobility in the direction of $\boldsymbol{E}$ peaks at the speed $\frac{1}{2}(E/B)$ at the height where $(\nu_{in}/\Omega_i) = 1$ (i.e. at ~125 km), at which altitude the drift in the direction of $\boldsymbol{E}\times\boldsymbol{B}$ is also reduced to the same value, so that the ions drift at 45° to $\boldsymbol{E}\times\boldsymbol{B}$, towards the direction of $\boldsymbol{E}$.

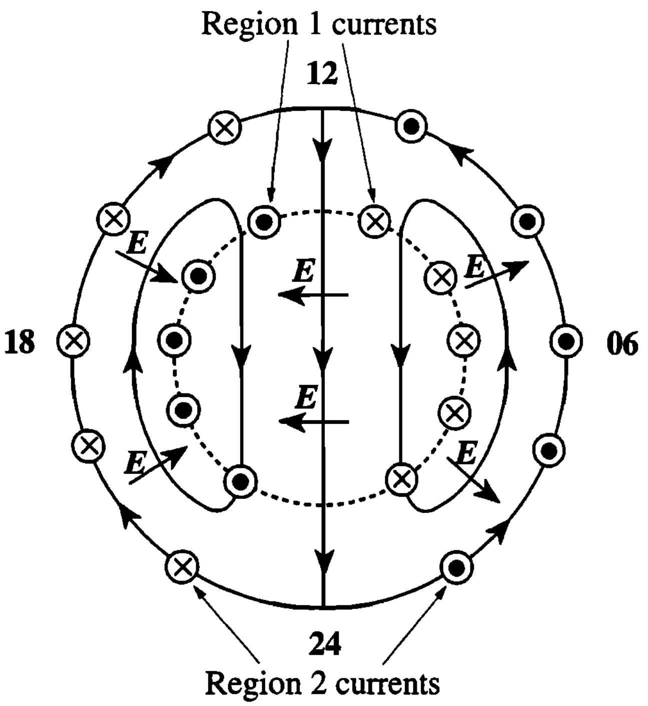

Figure 1. Schematic of Dungey-cycle flow mapped into the ionosphere, where the arrowed solid lines are the plasma streamlines, the short arrows give the direction of the electric field, and the dashed line is the open-closed field line boundary. The Hall current flows round the plasma streamlines opposite to the flow, while the Pedersen current flows in the direction of $\boldsymbol{E}$. The direction of FAC flow associated with the horizontal divergence of the latter currents is indicated by the circular symbols, where circled dots indicate upward currents out of the ionosphere, while circled crosses indicate downward currents into the ionosphere.

In principle a similar discussion also applies to ionospheric electrons, in terms of the ratio of the electron-neutral collision frequency to the electron gyrofrequency. However, this ratio remains small throughout the whole region of the ionosphere where appreciable plasma densities are present (above ~90 km). Thus the electrons $\boldsymbol{E}\times\boldsymbol{B}$ drift at all ionospheric heights. The immediate consequence is that a field-perpendicular electric current must flow in the lower ionosphere, whose density is

$$\boldsymbol{j}_\perp = \frac{ne\left(\frac{\nu_{in}}{\Omega_i}\right)}{\left(1+\left(\frac{\nu_{in}}{\Omega_i}\right)^2\right)} \left[\frac{\boldsymbol{E}}{B} - \left(\frac{\nu_{in}}{\Omega_i}\right)\frac{\boldsymbol{E}\times\boldsymbol{B}}{B^2}\right] \qquad (3)$$

$$= \sigma_P \boldsymbol{E} + \sigma_H \hat{\boldsymbol{B}} \times \boldsymbol{E} \;,$$

where n is the ion and electron number density (for simplicity we assume the dominance of one singly-charged ion species only), and $\hat{\boldsymbol{B}}$ is the unit vector along $\boldsymbol{B}$. The first term is the Pedersen current in the direction of $\boldsymbol{E}$, which is dominant above ~125 km where both species approximately $\boldsymbol{E}\times\boldsymbol{B}$ drift, but where the ions have some mobility in the direction of $\boldsymbol{E}$. The second term is the Hall current in the direction $-\boldsymbol{E}\times\boldsymbol{B}$ which is dominant below ~125 km where the electrons $\boldsymbol{E}\times\boldsymbol{B}$ drift but the ions become increasingly immobile. The two current densities are equal at ~125 km where $(\nu_{in}/\Omega_i)=1$, which is also approximately where the Pedersen current peaks (depending a little on the height profile of n). Upon integrating with altitude, the total height integrated field-perpendicular current intensity is thus

$$\boldsymbol{i}_\perp = \Sigma_P \boldsymbol{E} + \Sigma_H \hat{\boldsymbol{B}} \times \boldsymbol{E} \quad , \qquad (4)$$

where $\Sigma_P = \int dz\ \sigma_P$ is the height-integrated Pedersen conductivity, and $\Sigma_H = \int dz\ \sigma_H$ is the height-integrated Hall conductivity. In the sunlit ionosphere these conductivities are of order ~10 mho. On the nightside they depend on the intensity and energy of precipitating plasma particles from the magnetosphere, and may vary by at least an order of magnitude in either direction, with Hall conductivities exceeding Pedersen conductivities typically by factors of 2 to 4.

The implication of this discussion is that when the magnetosphere drives an ionospheric plasma through the neutral atmosphere, currents must flow in the lower ionosphere due to ion-neutral collisions. The $\boldsymbol{j}\times\boldsymbol{B}$ force of the currents just balances the neutral drag force of the atmosphere (the height integral of minus the RHS of Eq. 1), and consists of two components, one associated with the Pedersen current, the other with the Hall current. The $\boldsymbol{j}\times\boldsymbol{B}$ force associated with the Pedersen current just balances the drag force in the direction opposite to the $\boldsymbol{E}\times\boldsymbol{B}$ drift, while the force associated with the Hall current just balances the drag force in the direction opposite to $\boldsymbol{E}$ associated with the Pedersen mobility. Equal and opposite drag forces also act, of course, on the neutral gas, which are thus just equal to $\boldsymbol{j}\times\boldsymbol{B}$, and which tend to excite winds in the thermosphere. As just indicated, these forces have both a "Hall" component in the direction of $\boldsymbol{E}$, and a "Pedersen" component in the direction of $\boldsymbol{E}\times\boldsymbol{B}$, and despite the fact that they are of comparable magnitude, the "Pedersen" component is much more effective in exciting winds than the "Hall" component because the Pedersen currents flow at a somewhat higher altitude where the neutral densities are significantly less.

In addition to requiring a mechanical force to maintain the flow against neutral air drag, electromagnetic energy is also dissipated and heats the neutral gas. The height-integrated Joule heating rate per unit area of the ionosphere is $\boldsymbol{i}_\perp.\boldsymbol{E} = \Sigma_P E^2$ W m^{-2}, where we note that the Hall current is non-dissipative ($\boldsymbol{j}.\boldsymbol{E}=0$) and does not enter. These considerations inescapably imply that the ionospheric "load" must be coupled to a "generator" in the magnetosphere/magnetosheath via a large-scale current system, and that energy and momentum must flow from the latter to the former via Poynting flux and Maxwell field stress respectively.

We now turn specifically to consider the flow system associated with the Dungey cycle, shown in Fig. 1. In principle, if the ionosphere were uniformly conducting, the Hall current would close wholly within the ionosphere, flowing around the plasma streamlines ($\boldsymbol{E}\times\boldsymbol{B}$ drift paths) opposite to the direction of plasma flow. However, the Pedersen currents flowing in the direction of $\boldsymbol{E}$ cannot close within the ionosphere, but instead their divergence must be accommodated by a system of currents flowing into and out of the ionosphere along the field. The sense of those currents is indicated by the circled dot and cross symbols in Fig. 1, where circled dots indicate current flow out of the ionosphere, and circled crosses current flow into the ionosphere. These clearly provide a basic explanation of the Region 1-Region 2 currents described in the introduction. The Region 1 system flowing in the vicinity of the open-closed field line boundary is fed by Pedersen currents flowing from dawn to dusk across the polar cap, as well as by Pedersen currents flowing north-south in the auroral zone. The Region 2 currents ensure continuity of the auroral zone currents alone in the lower latitude regions of the flow cells, and consequently carry a lower total current than do the Region 1 currents, as previously noted.

Figure 1 may be used directly to estimate the total Joule heat production rate in the ionosphere. Using the fact that the ionospheric electric field is essentially curl-free (due to the strength and incompressibility of the ionospheric magnetic field) and hence describable as the gradient of a scalar potential φ, together with the divergence-free condition for the total current $\boldsymbol{j}$, we find

$$R_J = \int_V \boldsymbol{j}.\boldsymbol{E}\ d\tau = -\int_V \boldsymbol{j}.\nabla\varphi\, d\tau = -\int_S \varphi\ \boldsymbol{j}.d\boldsymbol{S} \quad , \qquad (5)$$

where the final integral is over the upper surface of the ionosphere such that the total current $\boldsymbol{j}$ which appears within it is effectively the FAC flowing into and out of the ionosphere. If we then take the outer streamline in Fig. 1 to be at zero volts, such that the focus of the dawn flow cell is

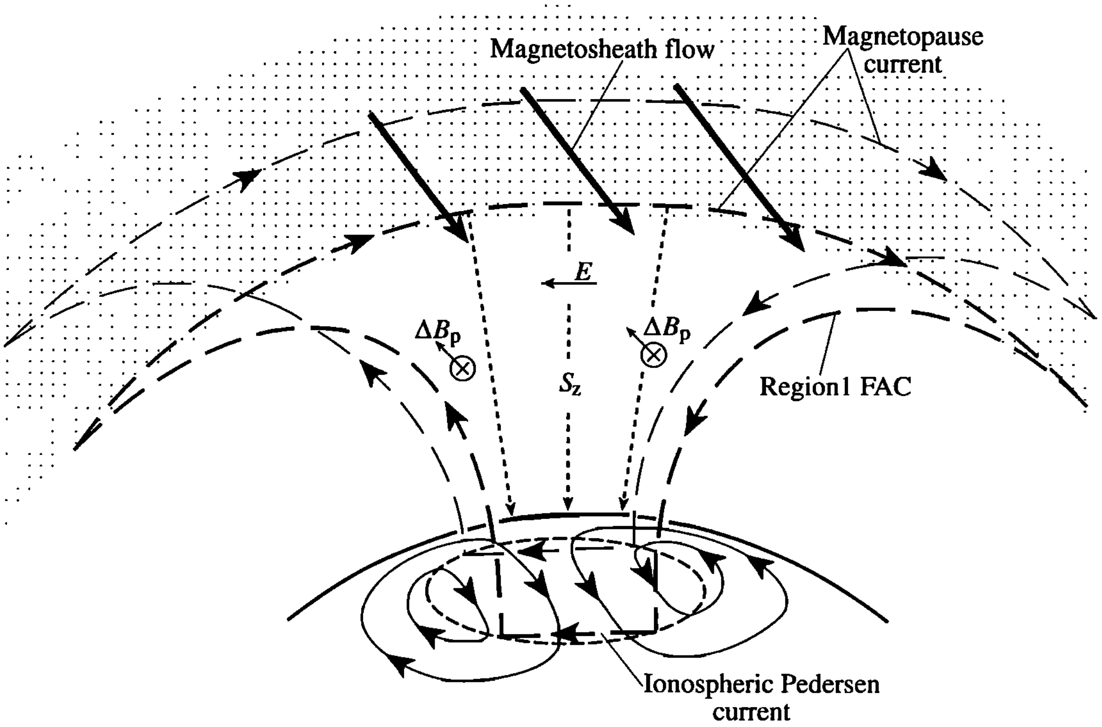

Figure 2. Sketch of the polar cap current circuit (long dashed lines), in which the dawn-to-dusk Pedersen current in the ionosphere closes in the magnetopause current via Region 1 FAC flowing on the outer surface of the plasma sheet. The current circuit produces sunward-directed perturbation magnetic fields ΔB_p in the polar region (in the northern hemisphere), which, combined with the dawn-to-dusk electric field E associated with the flow, produces a net downward Poynting flux S_z of electromagnetic energy into the ionosphere (short-dashed lines).

at potential $\varphi = \Phi/2$ volts, while that of the dusk cell is at $\varphi = -\Phi/2$ volts, where Φ is the total transpolar voltage associated with the flow, then it is easy to see that $R_J \approx I\Phi$ W, where I is the total Region 1 current. For typical values $\Phi \approx 50$ kV and $I \approx 2$ MA we thus have $R_J \approx 10^{11}$ W. This represents ~10% of the energy consumed by the magnetosphere in cislunar space, and ~1% of the total kinetic energy of the solar wind which is incident on the magnetospheric cross-section. With regard to the total force exerted on the ionosphere by the magnetosphere, it is easy to show that if the conductivities are uniform, the total $j \times B$ force integrated around each ionospheric streamline is zero. The net force on the ionosphere will thus depend upon the distribution of conductivity, and will in general be directed sunward, due to the larger conductivity, and hence drag, in the auroral zone. The total antisunward force acting on the polar cap ionosphere is typically ~10^8 N, comparable to the total ram pressure of the solar wind acting over the magnetospheric cross-section, while the total sunward force acting on the auroral zone ionosphere is typically about double this.

3. MAGNETOSPHERE-IONOSPHERE CURRENT CIRCUITS

As indicated above, the currents flowing in the ionospheric "load" must close in a magnetosphere-magnetosheath "generator", involving a large-scale system of FACs flowing between these regions. Figure 2 shows the large-scale circuit associated with the polar cap current, where the ionospheric Pedersen currents close in the tail lobe magnetopause via Region 1 FACs flowing on the outer surface of the plasma sheet. The magnetopause currents are the "generator" currents where $j.E < 0$, the ionospheric Pedersen currents are the "load" where $j.E > 0$, and there is a net downward Poynting flux from one region to the other via the perturbation magnetic field produced by the current circuit. In the northern hemisphere the perturbation fields are directed opposite to the flow, while in the southern hemisphere they are directed parallel to the flow. These fields constitute the "transverse magnetic disturbances" originally observed by Zmuda *et al.* (1966). Just above the conducting layer of the ionosphere the field perturbation due to the Pedersen current is $\Delta B_P = \mu_0 \Sigma_P E$, so that the vertical component of the Poynting vector is $S_z = (E\,\Delta B_P)/\mu_0 = \Sigma_P E^2$, i.e. S_z is just equal to the ionospheric Joule heating rate per unit area of the ionosphere, as required by energy conservation (Poynting's theorem). In mechanical terms, the magnetosheath is slowed by the sunward $\boldsymbol{j} \times \boldsymbol{B}$ force of the magnetopause current and provides energy to the electromagnetic field. The stress is fed by the tilted field to the ionosphere, where the $\boldsymbol{j} \times \boldsymbol{B}$ force balances the frictional drag on the ions and in turn accelerates the neutral atmosphere in the direction of the plasma flow.

In general, because currents in space plasmas are always essentially divergence-free (otherwise the build-up of space charge implied by the continuity equation would be enormous), we can consider current tubes (like flux tubes of the magnetic field) around which the total current dI is constant. In some regions of the tube $\boldsymbol{j}.\boldsymbol{E} > 0$ and energy flows from the field to the plasma, while in others $\boldsymbol{j}.\boldsymbol{E} < 0$ and the energy flows from the plasma to the field. If we integrate $\boldsymbol{j}.\boldsymbol{E}$ over the whole tube, it is easy to show that the integral is equal to dI times the emf around the tube, where the latter is equal to the rate of change of magnetic flux through the tube by Faraday's law (Cowley, 1991). In the steady state, therefore, the integral of $\boldsymbol{j}.\boldsymbol{E}$ over the tube is zero, and the "generators" in the tube exactly balance the "loads". Then the Poynting flux output from the generator regions is equal to the Poynting flux input into the loads, as implied by Fig. 2, though in general there is no guarantee that the Poynting flow will be direct. In the time-dependent case, however, the loads and generators need not balance, in which case energy is either stored or extracted from the changing field configuration. If the loads predominate, such that the volume integral of $\boldsymbol{j}.\boldsymbol{E}$ is positive, then the magnetic flux threading the current circuit decreases with time, while if the generators predominate, such that the integral of $\boldsymbol{j}.\boldsymbol{E}$ is negative, then the flux threading the current circuit increases with time.

One word of caution should be introduced, however, before concluding the above general discussion of energy flow, concerning frames of reference. It is obvious that the kinetic energy of an element of the plasma depends upon the frame of reference, and that an element which is gaining kinetic energy in one frame may be losing it in another. Similarly, the electric field in the plasma, given approximately by $\boldsymbol{E} = -\boldsymbol{V} \times \boldsymbol{B}$ when collisions are absent, is frame-dependent, such that the Poynting flux is also frame-dependent, and a $\boldsymbol{j}.\boldsymbol{E}<0$ "generator" region in one frame may transform into a $\boldsymbol{j}.\boldsymbol{E}>0$ "load" in another. While the laws of physics, including Maxwell's equations, Poynting's Theorem, and conservation of energy, are of course valid in any frame, such that the above discussion of energy flow can be applied equally to any frame, and will make equal physical sense in any frame, it should therefore be understood that the physical terms of that discussion may well change from one frame to another. In discussing overall energy flow, therefore, we need to choose, and stick to, a particular frame of reference. Throughout this paper we choose the (non-rotating) rest frame of the Earth. While perhaps parochial, this choice nevertheless has virtues for terrestrial observers.

Having discussed above the flow of energy in the polar cap current circuit (in the Earth's frame), we now turn to the current circuit associated with the auroral zone. Geometrically it is clear that the Region 1 current must flow in the outer part of the plasma sheet, while the Region 2 current must flow in the inner part of the plasma sheet and ring current region. To examine the closure of the latter current, therefore, we must consider the current flow in the hot plasma of the quasi-dipolar magnetosphere. The essential physical principle to be applied is that the FAC flowing into or out of the ionosphere must just balance the flux-tube integrated divergence of the field-perpendicular current carried by the hot magnetospheric plasma, such that the divergence of the total current is zero. From the continuity equation, this is exactly equivalent to considering the flow of charge which must take place along the field lines in order to maintain the charge-neutrality of the hot plasma, which is an equivalent and sometimes simpler way to think about the problem. Let us therefore consider the contributions to the field-perpendicular current in the magnetosphere, that is to say plasma magnetisation and particle drifts, and also equivalently consider the particle motions which may produce charge-separation in the plasma. First, magnetisation currents are exactly divergence-free (given by the curl of the magnetisation), and therefore make no contribution to the discussion. Since these currents are associated with particle gyration around the field lines at a microscopic level, they also clearly cannot relate to charge separation in the plasma. Second, turning to the drifts, the $\boldsymbol{E} \times \boldsymbol{B}$ drift at any point is the same for all particles such that it produces no current at all in a charge-neutral plasma. Equally clearly this drift cannot produce charge-separation either. Third, inertia currents and drifts associated with the changing bulk velocity in the plasma are generally (though not invariably) small in the inner magnetosphere. It therefore becomes clear that the principal origins of current divergence and hot plasma charge-separation in the inner magnetosphere must be associated with the gradient and curvature drifts of the magnetospheric particles.

We will now outline some basic physical ideas following the discussion given by Wolf (1983), which is in turn based on the earlier ideas presented by Schield *et al.* (1969). For

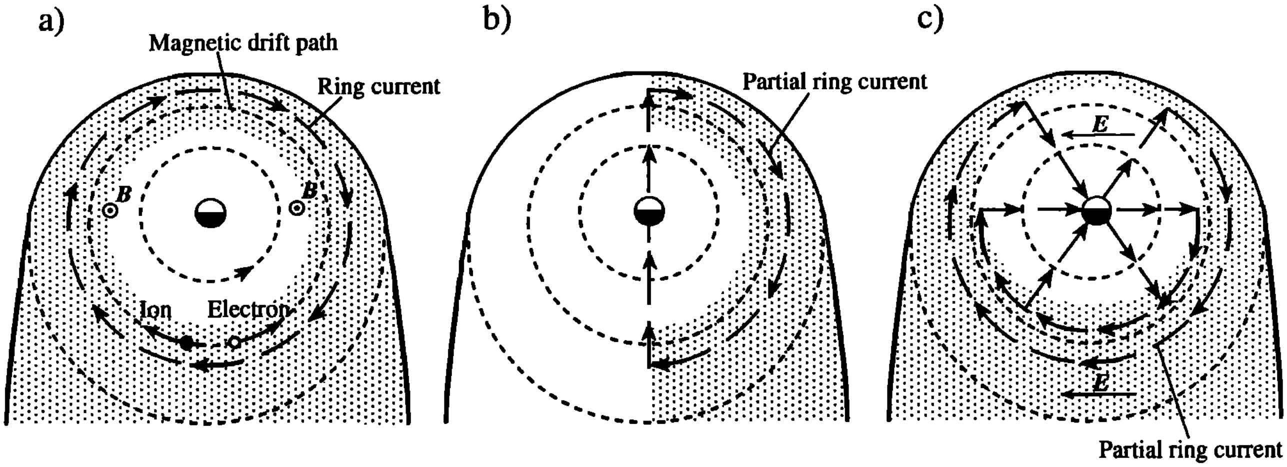

Figure 3. Sketches of the equatorial magnetosphere showing the FAC flow which connects the magnetospheric and ionospheric current systems (long-dashed lines) required by current continuity, for various spatial distributions of hot ring current plasma (dotted regions). The short-dashed lines represent the magnetic drift paths of ions and electrons, with ions drifting to the west and electrons to the east. In sketch (a) the plasma is distributed uniformly around the drift paths, such that the drift current is divergence-free in the magnetosphere and no FAC flows. In sketch (b) the initial plasma distribution has higher densities at dawn than at dusk, such that the partial ring current at dawn must close in the ionosphere via downward FACs at midnight and upwards FACs at noon. Sketch (c) shows the situation produced from an initial equilibrium by an interval of sunward flow imposed by a dawn-to-dusk electric field ***E***. A partial ring current is formed centred on midnight, which closes via downward FAC at dusk and upward FAC at dawn. After Wolf (1983).

simplicity, this discussion neglects the time-varying magnetic field perturbations due to the hot plasma currents, which is correct only for a low-beta plasma. Nevertheless, the essential physical ideas remain valid in the more general case. In Fig. 3 we thus view the equatorial plane of the inner magnetosphere and its hot plasma population (dotted areas), where the plasma is assumed initially charge-neutral. For simplicity we first assume that there is no $\boldsymbol{E} \times \boldsymbol{B}$ drift of the plasma, so that the particles simply move along gradient and curvature drift paths, ions to the west and electrons to the east. These paths are shown by the short-dashed lines. For particles with 90° pitch angle these paths are contours of constant field strength. For particles with 0° pitch angle they are contours of constant field line length. For a population maintained isotropic by strong pitch-angle scattering, as generally assumed in modelling, they are lines of constant flux tube volume per unit magnetic flux, $V = \int ds/B$ (the integral extends over the length of the flux tube from the southern to the northern ionosphere). Figure 3a illustrates the situation in which the hot plasma flux tube content per unit magnetic flux is constant around each drift path. In this case the macroscopic plasma configuration does not change at all as the individual particles drift. Consequently, no charge-separation of the hot plasma occurs, the hot plasma current (a westward ring current) is divergence-free around the drift-paths in the magnetosphere, and there is no requirement for current flow to or from the ionosphere. Suppose instead, however, that the initial hot plasma density is higher at dawn than at dusk, as shown in Fig. 3b. Now the drift of ions to the west and electrons to the east would result in the development of a positive space charge in the plasma near midnight, and a negative space charge near noon. We therefore require a flux of cold electrons out of the ionosphere to neutralise the positive space charge at midnight (or hot ions in), and a flux of cold ions out (or hot electrons in) at noon. In current circuit terms, then, a net partial ring current flows westward in the hot plasma in the dawn magnetosphere, which is fed by an upward FAC at noon, and is closed by a downward FAC at midnight, as shown by the long-dashed lines in the figure. These FAC directions would be reversed if the hot plasma was more dense at dusk than at dawn.

These are hypothetical situations. The question we have to ask concerns the nature of the plasma distributions which would be set up by Dungey-cycle flow. Suppose we start

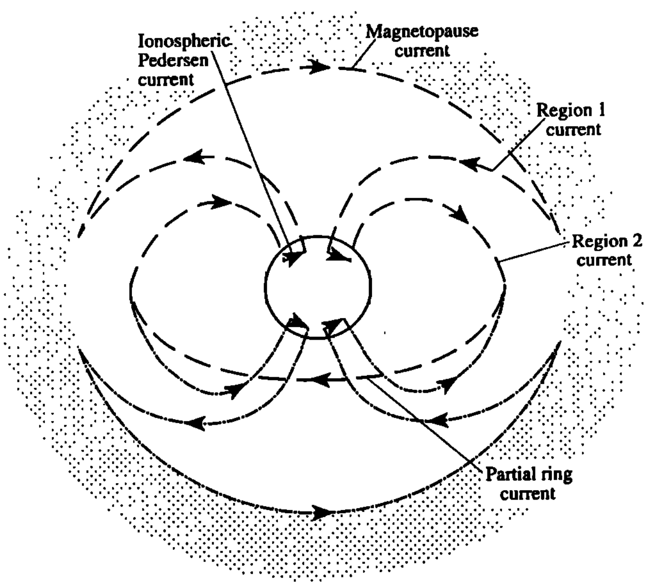

Figure 4. Sketch of the overall auroral zone current circuit looking at the Earth from the tail, showing both the northern (dashed lines) and southern (dot-dashed lines) branches of the circuit.

with an equilibrium distribution with no FAC such as that shown in Fig. 3a, set up by some earlier episode of hot plasma inflow from the tail, in which the hot plasma content per unit magnetic flux on each drift path decreases as we move towards the Earth. If we then apply a dawn-to-dusk electric field across the system, the $\boldsymbol{E}\times\boldsymbol{B}$ drift will displace the plasma sunward everywhere, with the result shown in Fig. 3c. On each drift path the flux tube content is now maximum at midnight and minimum at noon. The maintenance of charge neutrality, or equivalently current continuity, therefore requires current flow into the ionosphere at dusk, and out of the ionosphere at dawn. That is, we require a FAC flow in the same sense as the Region 2 current. We therefore infer that the latter currents are closed in the inner magnetosphere by a westward partial ring current flowing in the sunward-propagating inner plasma sheet population. We note that this inference is in accord with the equatorial current distribution determined from magnetic measurements made by the AMPTE-CCE spacecraft (Iijima *et al.*, 1990). The overall auroral zone current circuit is therefore as shown in Fig. 4. The magnetospheric partial ring current flowing in the nightside inner plasma sheet region closes in the ionosphere by Region 2 FACs, the current then flows across the auroral zone ionosphere as north-south Pedersen currents, then out as Region 1 currents flowing in the outer layers of the plasma sheet to the magnetopause, where it then closes in the magnetosheath plasma. In the steady state the magnetosheath "generator" feeds Poynting flux into both the dissipative ionospheric Pedersen currents, and into the energy stored in the compressed and heated hot magnetospheric plasma. In the absence of the magnetosheath "generator", the circuit could also be powered by the decay of the tail magnetic flux which threads through it.

The above discussion is qualitative. In reality (and in modelling) the flow in the system must adjust in order to ensure that the divergence of the hot plasma current in the magnetosphere is matched by the divergence of the horizontal current in the ionosphere. From Eq. 4, the FAC density into the ionosphere required by the continuity of the field-perpendicular ionospheric current is

$$j_{\parallel_i} = \nabla_h . \boldsymbol{i}_\perp = \nabla_h . (\Sigma_P \boldsymbol{E} + \Sigma_H \hat{\boldsymbol{B}} \times \boldsymbol{E}) \ , \qquad (6)$$

where ∇_h is the two-dimensional horizontal gradient operator, and for simplicity we have assumed a vertical polar magnetic field. Current continuity in the magnetosphere requires

$$j_{\parallel_i} = -\tfrac{1}{2}\int_V d\tau \ \ \mathrm{div}\boldsymbol{j}_\perp = -\tfrac{1}{2} B_i \int \frac{ds}{B} \mathrm{div}\boldsymbol{j}_\perp \ , \qquad (7)$$

where the integrals extend over the whole magnetospheric flux tube from the southern to the northern ionosphere, $\boldsymbol{j}_\perp$ is the field-perpendicular magnetospheric plasma current density, B_i is the ionospheric field strength, s is distance along a field line, and we have assumed equal parallel current density into the ionosphere in both hemispheres. With the neglect of the inertia current we have

$$\boldsymbol{j}_\perp = \frac{\boldsymbol{B}\times\nabla p}{B^2} \ ,$$

where p is the plasma pressure (assumed isotropic and hence constant along a field line). Substitution into Eq. 7 can then be shown to yield

$$j_{\parallel_i} = -\frac{B_i}{2B} \hat{\boldsymbol{B}} . \nabla p \times \nabla V = -\frac{B_i}{2BV^{5/3}} \hat{\boldsymbol{B}} . \nabla (pV^{5/3}) \times \nabla V \ , \qquad (8)$$

where the V is the flux tube volume per unit magnetic flux as before, and the gradients can be evaluated at any point on the field line in the magnetosphere. Equating $j_{\parallel_i}$ between Eqs. (6) and (8) then yields the condition for continuity of the magnetosphere-ionosphere current, which can be solved for the self-consistent electric field and flow. This equation was first derived by Vasyliunas (1970), and

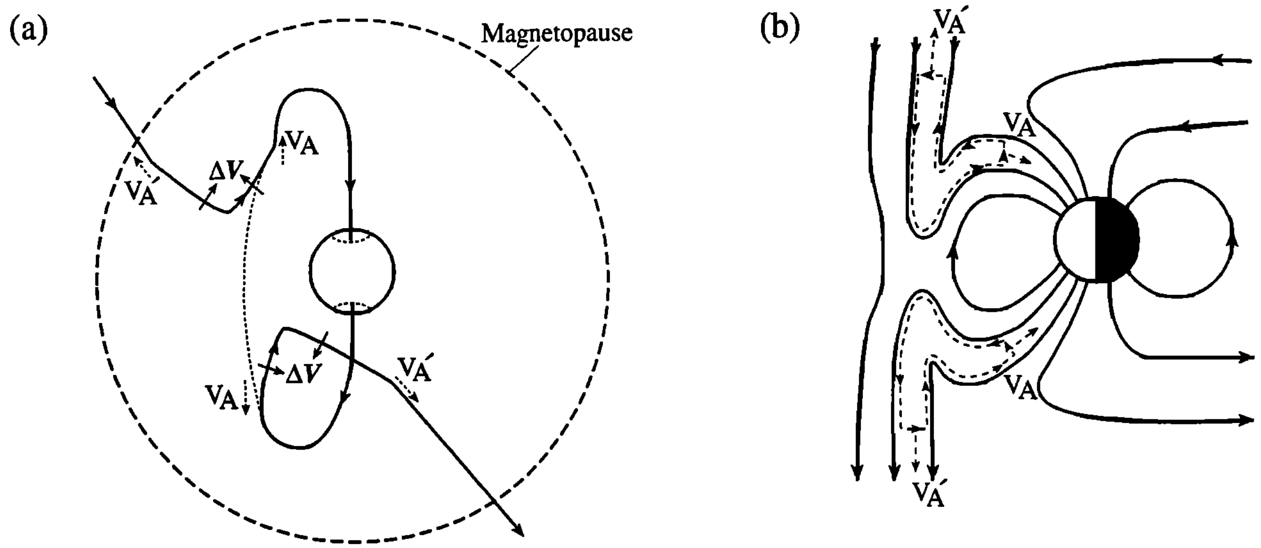

Figure 5. (a) Sketch of newly-opened field lines following subsolar reconnection with an IMF having negative Z and positive Y components, showing the field tilting effects in the magnetospheric and magnetosheath boundary layers due to the tension in the magnetic field. The view is looking at the Earth from the direction of the Sun. The short solid arrows marked ΔV show the associated velocity perturbations transverse to the magnetic field, while the short dashed arrows marked V_A indicate the propagation of the disturbance along the open field lines at the Alfvén speed. (b) View projected onto the noon-midnight meridian, showing the associated FAC and cross-field closure current systems (arrowed dashed lines) propagating along the open field lines at the Alfvén speed.

is the condition on which self-consistent models such as the Rice convection model are based (Wolf, 1983). The physical content of the equation is equivalent to the discussion which we made in relation to Fig. 3. The final form of Eq. 8 is interesting because it shows that in any region where $pV^{5/3}$ is a constant (as will result from lossless adiabatic convection from a uniform source), there will be no FAC flow between the magnetosphere and ionosphere.

4. CUSP CURRENTS

Having discussed the Region 1/2 current system associated with large-scale twin-cell convection, we now turn to look at the origins of the third FAC component mentioned in the introduction, namely the cusp currents, which flow on open field lines poleward of the Region 1 system on the dayside. These currents relate to the stresses exerted on newly-opened field lines following reconnection at the magnetopause, and the consequent motion of the open flux tubes. Two factors influence this motion, namely the tension in the reconnected magnetic field lines, and the flow of the magnetosheath plasma around the magnetopause away from noon. For near-subsolar reconnection with a southward-pointing IMF, the field tension effect will be the most important initially, while the effect of the flow will exert itself as the magnetosheath plasma becomes super-Alfvénic in the downstream region. An important consequence of the initial dominance of the field tension force is that the motion of the newly-opened flux tubes responds strongly to the Y component of the IMF, as first discussed by Jørgensen *et al.* (1972). Figure 5a shows open field lines shortly after subsolar reconnection has taken place with a magnetosheath field which has positive Y and negative Z components, in a view looking towards the Earth from the direction of the Sun. In the magnetosphere, the field tension force pulls the open lines towards dawn in the northern hemisphere, and simultaneously towards dusk in the southern hemisphere, such that the field tilts over in the boundary layer towards the direction of the magnetosheath field outside. This disturbance propagates down the open field lines as an Alfvén wave, which we note is the MHD mode specifically associated with the propagation of field-aligned current. A similar disturbance also propagates out into the magnetosheath, which results in the sheath field being

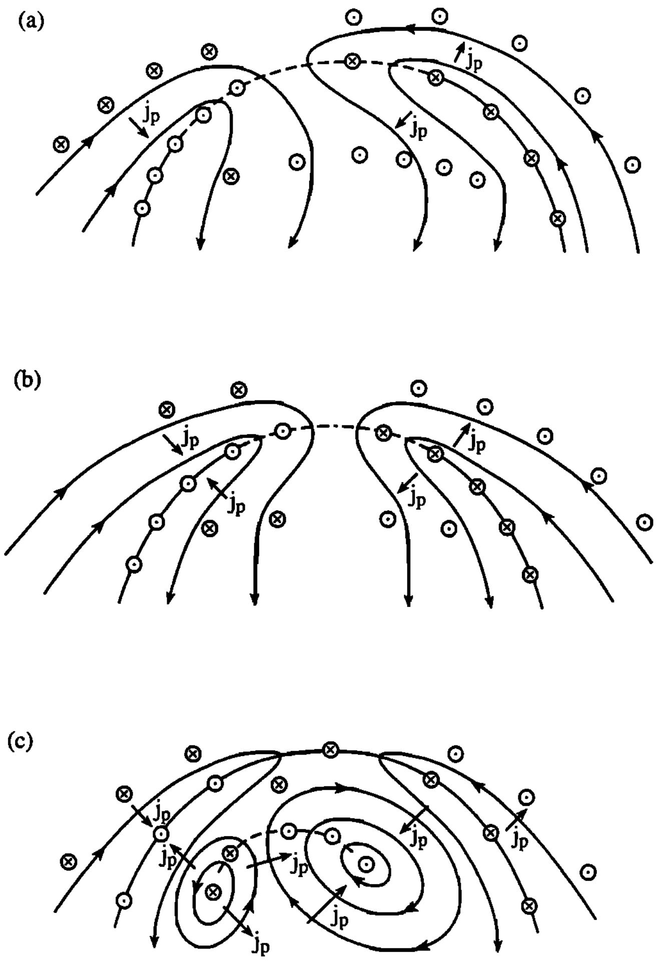

Figure 6. Sketches looking down on the northern hemisphere ionosphere showing the plasma streamlines (arrowed solid lines) for various IMF orientations, together with the sense of FAC flow. Circled dots indicate upward flow, and circled crosses downward flow. The short arrows marked j_p indicate the closure Pedersen currents in the ionosphere. The solid lines without arrows indicate the open-closed field line boundary, while the dashed lines map along the field to the magnetopause reconnection sites. Sketch (a) is for an IMF with negative Z and positive Y components, (b) for negative Z and near-zero Y, and (c) for positive Z and positive Y (in the presence of continued tail reconnection).

pulled towards the magnetospheric field direction. The form of the current system is shown schematically in the side view in Fig. 5b, and consists of a system of oppositely-directed sheets of FAC in both hemispheres, bounding the region of tilted field, and terminated by propagating field-transverse inertia currents in the "head" of the wave. After ~2 min the magnetospheric "head" arrives at the ionosphere, and (after a bounce or two due to the impedance mis-match between the wave and the ionosphere) establishes a westward flow of open field lines in the northern cusp, and a similar eastward flow in the southern cusp. At ionospheric heights the flow is associated with paired sheets of FAC as indicated in Fig. 5b, which in the northern hemisphere are directed downward, into the ionosphere, on the equatorward boundary of the cusp (essentially the open-closed field line boundary), and upward, out of the ionosphere, on the poleward boundary, and vice versa in the southern hemisphere.

The dayside pattern of FAC in the northern hemisphere for steady reconnection with IMFs of various orientations is shown in Fig. 6. The situation for positive Y and negative Z is shown in Fig. 6a, where, as just discussed, the cusp currents are predominantly downward on the equatorward border and upward on the poleward border, and are closed by poleward-directed Pedersen currents in between. The flow between the sheets is predominantly westward, and thus associated with an eastward Hall current which provides most of the magnetic effect seen on the ground. We note that the poleward cusp FAC sheet will be co-located with the region where the plasma flow rotates from westward to antisunward. It thus represents the point on the flow streamlines where the field tension effect ceases to be dominant and gives way to the effect of the anitsunward flow of the magnetosheath plasma (Saunders, 1989).

For an IMF with negative Y and negative Z, the sense of the east-west flow asymmetry is reversed from that shown in Fig. 6a, together with the predominant sense of the cusp FAC, and is not shown here. Rather, in Fig. 6b we show the symmetrical situation for negative Z and near-zero Y. Here the newly-opened tubes are swept symmetrically away from noon towards dawn and dusk by the magnetosheath flow before turning antisunward. The cusp currents are correspondingly symmetrical, with the third FAC sheet at highest latitude having opposite polarity to the Region 1 current.

Figure 6c illustrates the fact that "cusp" currents also flow when IMF Z is positive. Here we show, as an example, the simultaneous presence of a "reversed" twin vortex flow on open field lines driven by lobe reconnection in the presence of positive IMF Y, together with the continued presence of "normal" twin-vortex flow at lower latitudes driven by open flux closure in the tail, such that the open-closed field line boundary contracts. The "reversed" twin vortex, first inferred from ground magnetic measurements by Maezawa (1976), is associated with a paired FAC system, termed the "NBZ" currents, in which the FAC flows downwards in the dusk vortex, and upwards in the dawn vortex (McDiarmid *et al.*, 1980; Saflekos and Potemra, 1980). The origins and

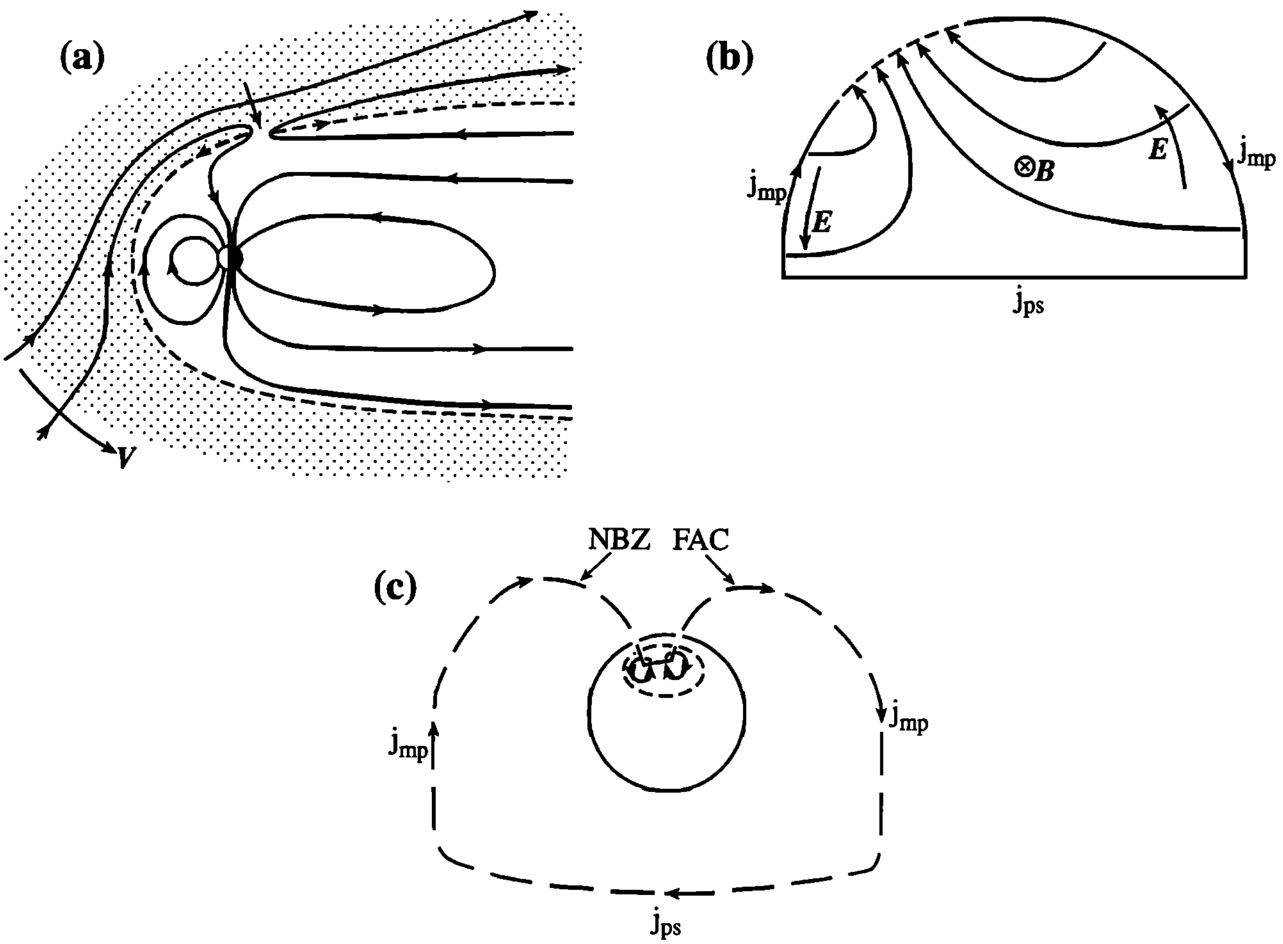

Figure 7. Sketches showing the fields and flows associated with single-lobe reconnection for an IMF with positive Z, positive Y, and negative X components. In sketch (a) reconnection in the northern lobe produces "new" open field lines draped over the dayside (without changing the amount of open flux), which are subsequently swept into the tail by the magnetosheath flow (preferentially on the dawn side in this case). Sketch (b) shows a cross-section through the northern tail looking towards the Earth, showing the flow of open flux from the sides of the tail (preferentially the dawn side) to the duskside lobe magnetopause reconnection site. The current flows clockwise around the northern lobe. Sketch (c) shows the "NBZ" FACs which flow into and out of the central regions of the "reversed" polar cap vortices, and which close through the flank magnetopause and plasma sheet.

closure of this system are illustrated in Fig. 7, where for simplicity we have neglected the effects of simultaneous tail reconnection. In Fig. 7a single-lobe reconnection in the northern hemisphere. produces "new" open flux tubes draped over the dayside magnetopause, which initially contract sunward due to the field tension (also moving to dawn or dusk in the presence of an IMF Y component), and are then swept into the tail by the magnetosheath flow. Figure 7b shows the flow in a cross-section through the northern hemisphere tail lobe looking towards the Earth, such that the magnetopause current flow is clockwise from dusk to dawn, closing from dawn to dusk in the plasma sheet. For the case with a positive IMF Y component as shown (as in Fig. 6c), the lobe reconnection site will be located preferentially on the dusk side of the tail in the northern hemisphere, while the "new" open field lines will be swept preferentially towards dawn. The open tubes then flow from the flank magnetopause, where $\boldsymbol{j}.\boldsymbol{E}$ is negative and $\boldsymbol{j} \times \boldsymbol{B}$ slows the magnetosheath plasma flow, into the reconnection site at higher latitudes, where $\boldsymbol{j}.\boldsymbol{E}$ is positive.

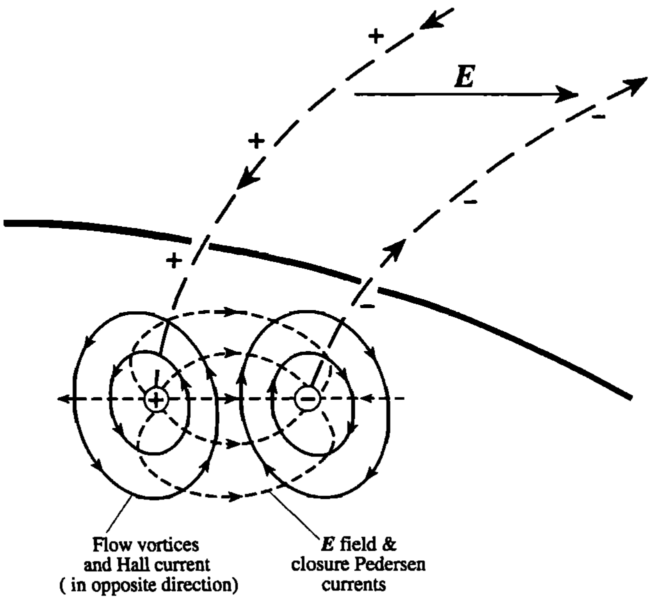

Figure 8. Sketch showing the electric field (arrowed short-dashed lines) and flow patterns (arrowed solid lines) in the northern hemisphere associated with a matched pair of oppositely-directed FACs (long-dashed lines). The FACs are closed in the ionosphere by the Pedersen currents flowing in the direction of the electric field. The plus and minus symbols indicate the senses of the slight space charge distributions associated with the electric field.

This flow corresponds to the antisunward part of the "reversed" twin vortices which appear in the ionosphere. The "NBZ" currents then tap part of the tail lobe current system, as shown in Fig. 7c, and thus close through the magnetopause "generator" currents on the tail flanks, and then through the essentially "inactive" (in this case) plasma sheet. Poynting flux flows from the tail flank magnetopause into the polar ionosphere.

5. TRAVELLING CONVECTION VORTICES

Reconnection between the IMF and the terrestrial field is not the only mechanism by which the solar wind may perturb and transfer momentum into the magnetosphere, though it is usually the most important. A second class of phenomena, termed "travelling convection vortices" (TCVs) are also observed (e.g. Friis-Christensen *et al.*, 1988), in which one or more east-west aligned pairs of oppositely-directed flow vortices propagate through the dayside ionosphere east or west away from noon at high latitudes. Each vortex has a spatial scale of ~1000 km, such that at any instant the twin vortices encompass several hours of local time, and they propagate over a few tens of minutes at phase speeds of 5 km s^{-1}. From our previous discussion it is evident that an ionospheric flow vortex must be associated with FAC flow at its centre. In the northern hemisphere, the FAC flows upward from the centre of a clockwise vortex, and downward into the centre of an anticlockwise vortex (and vice versa in the southern hemisphere). The basic system of ionospheric electric field and flow for such a system of paired currents is shown in Fig. 8. The FAC is closed in the ionosphere by the Pedersen current driven by an electric field which is dipolar in form, such that the region of downward current is associated with a (slight) net positive space charge, while the region of upward current is associated with a (slight) net negative space charge. The flow then consists of a pair of oppositely-directed vortices, around which the Hall current flows in the direction opposite to $\boldsymbol{E}\times\boldsymbol{B}$. For a vertical field, the magnetic effects of the FAC and the Pedersen currents exactly cancel under the ionosphere, such that the magnetic disturbance on the ground is dominated by the Hall current vortices. Typical FACs associated with each vortex in observed events are a few hundred kA.

While the basic form of TCVs at ionospheric heights is thus reasonably well understood, their physical origin as manifestations of solar wind-magnetosphere coupling at large distances remains to be clarified. Most theoretical discussion has centred on the effect of sudden changes in compressive plasma pressure in the magnetosheath, but while some of these events are associated with precursory changes of the dynamic pressure in the solar wind, this is by no means always the case. Indeed, Sibeck *et al.* (1999) have recently discussed one event which was associated with the interaction between the magnetosphere and a tangential discontinuity propagating in an otherwise undisturbed solar wind. This interaction produced a "hot flow anomaly" event in the dawn magnetosheath, and a sudden localised expansion of the equatorial magnetopause by ~5 R_E, which propagated tailward. It therefore appears that the TCV phenomenon can have more than one precursory signature in the solar wind. Whatever the origin of the pressure change and boundary motion, however, we may still enquire how the system of paired FACs come to be generated. The first simple thing we can say is that they are not generated in a direct way by compressions or rarefactions of the magnetosphere. A uniform contraction or expansion of the magnetosphere would produce almost no field or flow effect at ionospheric heights, because the field there is strong and almost incompressible. Equivalently, we may say that compressive (fast mode) MHD waves propagating in the magnetosphere are almost perfectly reflected by the ionosphere. We therefore must consider the effect of pressure fronts propagating over the

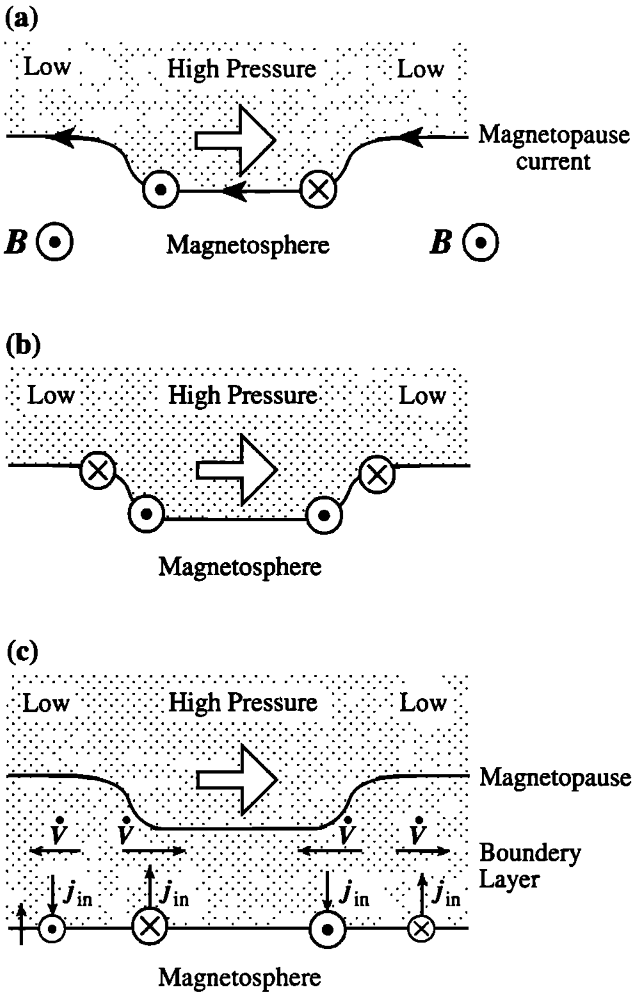

Figure 9. Sketches showing proposed FAC patterns associated with a single antisunward-propagating (left to right) compressive in-out motion of the magnetopause. The plane of the diagrams is the equatorial plane, such that the magnetospheric field points outwards. The dotted regions correspond to the high-density magnetosheath (upper two diagrams) and boundary layer (lower diagram) regions. Circled dots indicate current flow away from the equator towards the ionosphere in both hemispheres, while circled crosses indicate current flow towards the equator away from the ionosphere in both hemispheres. The former FACs are associated with a clockwise flow vortex in the plane of the sketch, while the latter are associated with an anticlockwise flow vortex. Sketch (a) follows the discussion of Glassmeier (1992), sketch (b) is after Kivelson and Southwood (1991), while sketch (c) is after Lühr *et al.* (1996). In the latter sketch we also show the directions of the inertia currents in the boundary layer, and the associated accelerations ($\dot{\boldsymbol{V}}$) of the plasma.

magnetopause which may generate vortical flows associated with FAC, which can propagate to the ionosphere as Alfvén waves.

Various suggested mechanisms are compared in Fig. 9, where we show the effect of a single compressive pulse propagating antisunward on the magnetopause. Each figure shows an equatorial cut through the dawn-side boundary region (for definiteness) perpendicular to the magnetospheric magnetic field, with the magnetosheath plasma (and compressive pulse) propagating from left to right. Circled dots indicate FAC flow away from the equator towards the ionosphere in both hemispheres, while circled crosses indicate FAC flow towards the equator and away from the ionosphere in both hemispheres. Figure 9a is due to Glassmeier (1992), who considers the continuity of the perturbed magnetopause current, and suggests one FAC (vortex) at each end of the perturbed region. Figure 9b is due to Kivelson and Southwood (1991), who consider the flow vorticity introduced at the magnetopause by the in-out boundary motions, and predict paired currents at each end. Both pictures therefore locate the FACs at the magnetopause, which will map to the open-closed field line boundary in the ionosphere. Recent work by Moretto and Yahnin (1998), however, shows that these currents are centred well inside the region of closed field lines, which then seems more in line with the suggestion of Lühr *et al.* (1996) shown in Fig. 9c. These authors suggest that the FACs are associated with the divergence of the inertia current at the density gradient at the inner edge of the magnetopause boundary layer. The inertia current is given by $j_\perp = \rho(\boldsymbol{B}/B^2)\times(\mathrm{d}\boldsymbol{V}/\mathrm{d}t)$, where $\boldsymbol{V}$ is the bulk velocity produced in the magnetospheric plasma by the propagating boundary perturbation. This produces a central pair of FACs which are opposite in sense to those proposed by Glassmeier (1992), plus two "outliers" of smaller amplitude. Overall, there is as yet no consensus on which of these proposed patterns, if any, matches the observed pattern for an impulsive compression, but it is clear that there exists sufficient diversity in the predicted outcome that some could be eliminated as the dominant effect.

6. SUBSTORM CURRENTS

The magnetopause reconnection processes which generate new open flux, whose effects were described in Sect. 4 above, initiate the growth phase of the reconnection cycle by causing the transfer of open flux from the dayside magnetopause to the tail lobes. Eventually, reconnection of the lobe field in the tail centre plane must also occur,

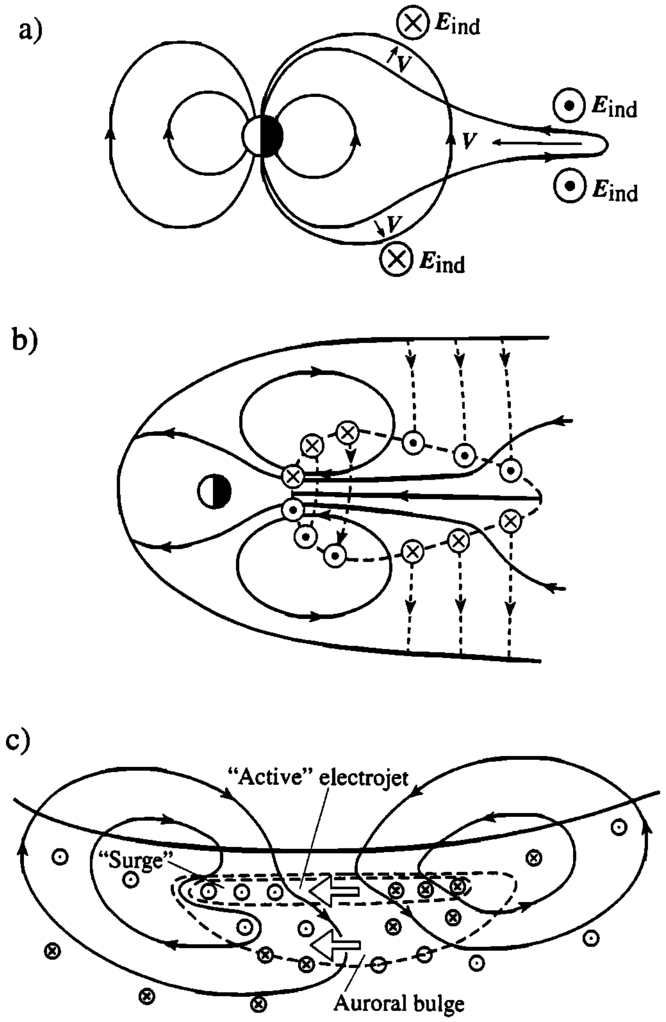

Figure 10. (a) Sketch showing the effect of substorm dipolarization on field lines in the near-Earth tail. Field lines move rapidly inwards near the equatorial plane and outwards at higher latitudes, associated with large cross-system inductive electric fields as shown. (b) Pattern of FACs in the near-Earth tail associated with substorm dipolarization within the dashed-line region. Circled dots indicate FAC flow away from the equator and into the ionosphere in both hemispheres, while circled crosses indicate FAC flow into the equator and away from the ionosphere in both hemispheres. The arrowed solid lines indicate plasma streamlines. (c) Sketch of the flow and currents in the conjugate ionosphere, where the outer dashed line indicates the dipolarized region, corresponding to the substorm expansion phase auroral bulge. The inner dashed line indicates the region of the "active" electrojet in the poleward part of the bulge. Arrowed solid lines are streamlines, and the pattern of FACs is again indicated by the circled dot and cross symbols.

forming new closed field lines in the plasma sheet which return towards Earth and close the Dungey cycle. The substorm expansion phase is believed to play a central role in this latter process, during which the key feature is an inward collapse or "dipolarization" of the growth phase-enhanced tail field, associated with bursts of rapid earthward flow in the plasma sheet (Baumjohann *et al.*, 1990; Angelopoulos *et al.*, 1992). It remains controversial whether the collapse is initiated by tail reconnection directly, or by some other process (e.g. an instability in the plasma sheet) which excites reconnection as a subsequent effect, though recent results from the Geotail spacecraft have shown that reconnection typically begins in the pre-midnight plasma sheet at down-tail distances between 20 and 30 R_E at times close to substorm expansion phase onset (Nagai *et al.*, 1998). In either case, the principal features of the expansion phase field and current effects are illustrated in Fig. 10. Figure 10a illustrates the expansion phase dipolarization of a field line. The growth phase field line is highly distorted away from a dipolar form by the presence of a thin but intense current sheet located in the plasma sheet in the near-Earth tail. After expansion phase onset these field lines collapse inwards at the equator, and outwards at high latitudes, to assume a more dipolar form associated with a much reduced tail current. These inductive effects do not, however, produce correspondingly large motions in the ionosphere, though to the extent that the process contributes to inward flux transport in the tail, it will excite twin-vortex Dungey-cycle flow.

The effect of this process on the tail current system is shown in Fig. 10b, which is a view of the equatorial plane of the magnetosphere. Here the azimuthally-limited dipolarized region is bounded by the heavy dashed line, and the circular symbols near its periphery indicate the direction of FAC flow, circled dots representing current flow away from the equator towards the ionosphere (in both hemispheres), and circled crosses current flow towards the equator away from the ionosphere. Two effects are illustrated (following the results of Lu *et al.*, 1997). Within the near-Earth tail (typically at distances from ~8 to ~30 R_E), the cross-tail current is reduced within the azimuthally-restricted dipolarized region, such that the tail current on either side is diverted along the field, towards the Earth on the dawn side of the region, and away from the Earth on the dusk side. This current flow just accommodates the shear in the field direction across the boundary between the dipolarized field inside the region and the remaining tail-like field outside. These FACs close through the ionosphere at one end (as further described below), forming the "substorm current wedge" first described by McPherron *et al.* (1973), and over the tail magnetopause at the other. They thus form a special type of auroral zone "Region 1" current, though in this case the ionospheric dissipation in the circuit is powered more by the emf provided by the reducing flux of the tail lobes, as outlined in Sect. 3, than by the magnetopause "generator". In this region the tail plasma flows rapidly inwards towards the Earth, where it is eventually "braked" by the increasing pressure of the compressed field and plasma at the outward-moving boundary between quasi-dipolar and tail-like fields, the "braking" being associated with a dawnward-directed inertia current in the plasma which contributes to the formation of the substorm current wedge in the near-Earth system (Shiokawa *et al.*, 1997). The hot injected plasma in the new quasi-dipolar region then forms a partial ring current centred near midnight which closes via "Region 2" currents, as described previously in Sect. 3.

In Fig. 10c illustrates conditions in the conjugate ionosphere, where, in addition to the above, we have also drawn on the discussion by Fujii *et al.* (1994) and Weimer *et al.* (1994). The outer dashed line corresponds to the dipolarized region in the tail, within which the accelerated plasma precipitates to form the substorm auroral bulge. This precipitation strongly enhances the conductivity of the bulge ionosphere to values (typically many tens of mhos) much higher than that of the surrounding region. The quadripolar pattern of FAC associated with the bulge follows that shown in Fig. 10b. In the poleward region the ("substorm wedge"-Region 1 type) current flows upwards on the dusk side of the bulge (corresponding to the "surge"), and downwards on the dawn side. These currents close principally via the "active" westward substorm electrojet flowing within the poleward part of the bulge (interior dashed line region), which carries typically ~1 MA of current. In the equatorward region the enhanced "Region 2" currents flow in the opposite sense, and presumably close as before principally via north-south Pedersen currents in the oppositely-directed FAC on its poleward side. The flow streamlines are shown by the solid lines, where we depict a distorted twin-cell flow centred around the "substorm wedge"-Region 1 currents, which is excited by the transport in the tail (Cowley *et al.*, 1998; Opgenoorth *et al.*, 1998).

The nature of the flow observed at ionospheric heights is, however, influenced by several complicating effects. The first is that magnetospheric and ionospheric flows can be partially decoupled by field-aligned voltages at intermediate (~1 R_E) heights, which may be required to drive the FACs themselves. Since FACs are mainly carried by highly mobile plasma electrons, upward FACs in particular are carried by hot magnetospheric electrons moving downwards into the mirror field geometry near the Earth. Field-aligned voltages may then be needed to draw sufficient current from the magnetospheric population. According to the formula first derived by Knight (1973), the upward current provided by magnetospheric electrons is

$$j_{\parallel} \approx j_0 \left(1 + \left(\frac{e\Phi_{\parallel}}{kT_e} \right) \right) , \tag{9}$$

where $\Phi_{\parallel}$ is the field-aligned voltage, T_e is the magnetospheric electron temperature, and j_0 is the maximum current that can be obtained without a voltage. The latter current corresponds to a full downward-going loss cone and an empty upward-going loss cone, and amounts to $\sim 1\ \mu\mathrm{A\ m}^{-2}$. However, the FACs observed flowing in the surge, for example, may be several times this value, thus requiring field-aligned voltages of order several times (kT_e/e), i.e. of order a few kV. Such voltages produce characteristic features in the electron distributions, variously known as "inverted-V" or "BPS"-type precipitation. The accelerated precipitating electrons may in turn significantly enhance the ionospheric conductivity through ionization of the neutral gas, and thus alter the pattern of FACs. A complex non-linear feedback between magnetosphere and ionosphere may then occur. The second complicating factor is that the flow at ionospheric heights tends to avoid the high-conductivity regions, such as that in the surge region shown in Fig. 10c. Radar data consistently show that the flow in such regions is suppressed relative to the surrounding regions, at least over few-minute intervals (e.g. Morelli *et al.*, 1995). One factor which could be involved is the field-aligned voltages just discussed, since these will close off magnetospheric equipotentials above the ionosphere. Another could be the effect of enhanced ion-neutral drag. The third complicating factor is the apparent "polarization" effects which lead to an overall eastward flow (i.e. equatorward electric field) and westward electrojet current within the high-conductivity bulge, as we have shown in Fig.10c. The usual story here is that the westward electric field in the bulge associated with the equatorward flow drives a poleward Hall current $\Sigma_H E_W$ across the high-conductivity bulge which cannot close by FAC along its poleward and equatorward borders. Instead, an equatorward polarization electric field is developed whose Pedersen current cancels the northward Hall current, such that the equatorward electric field is given by $E_S = (\Sigma_H/\Sigma_P)E_W$. The Pedersen current of the westward electric field and the Hall current of the southward electric field then add to produce a westward electrojet ("Cowling") current given by

$$i_C = \left(1+\left(\frac{\Sigma_H}{\Sigma_P}\right)^2\right)\Sigma_P E_W \quad . \qquad (10)$$

However, no obvious reason is given in this argument as to why the initial Hall current cannot close by FACs at the equatorward and poleward borders of the bulge, while at the same time the intense electrojet current which is formed thereby can close by FAC at its dusk and dawn "ends". As in Sect. 4, the answer to this question must surely lie in the conditions required for closure of the entire magnetosphere-ionosphere current circuit, and we note from Fig. 10b that the natural form of the magnetospheric FAC tends to favour the latter closure rather than the former. Whereas there has been much overall progress in understanding magnetosphere-ionosphere interactions in recent years, as evidence by the contents of former sections of this paper, there is clearly much left to be understood of the complexities of substorm electrodynamics.

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