Radar Observations of Convection in the Nightside High-Latitude Ionosphere.

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Adrian Grocott

Radio and Space Plasma Physics Group
Department of Physics and Astronomy
University of Leicester

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Abstract

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The work discussed in this thesis concerns the ionospheric flow response to different magnetospheric phenomena which occur under various interplanetary and geomagnetic conditions. This was undertaken primarily using the SuperDARN HF radar network located in the auroral regions of both hemispheres, but also utilised magnetometer and spacecraft data from a variety of sources. A detailed case study is first presented concerning the nature of convection in the nightside ionosphere during an isolated substorm. The results of this study unequivocally demonstrate that twin-vortex flow can be excited in association with substorm expansion, a phenomenon which has previously been the subject of some controversy. Two further case studies are presented of the ionospheric flows which exist during intervals of northward, but (negative) B_y-dominated IMF. Under these conditions it is found that the substorm cycle dies away, but that Dungey-cycle flow persists for many hours. During these intervals, strong ‘bursts’ of flow were observed in the nightside ionosphere, which are found to be associated with episodic reconnection in the distant magnetic tail. This study has shed new light on the magnetospheric response to an IMF of intermediate clock angles, revealing that the Dungey-cycle and the substorm cycle are not, in fact, synonymous. Finally, a discussion of ongoing and possible future work is given, which is suggested by the results of the studies described above, with initial results from a number of pilot studies being presented. The flows during a number of substorm events have been studied, which reveal that the excitation of flow appears to accompany substorm expansions in general. Also, a study of the flows during another interval of northward IMF now dominated by positive B_y provides an appropriate counterpart to the negative B_y case. This preliminary investigation reveals flows of a similar nature but with the expected opposite sense of B_y-asymmetry.
To Mum and Dad
Declarations

The research detailed in Chapters 4 and 5 of this thesis also appears in the following publications:


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Many people have helped in some way or another during my time as a PhD student. Whether that be in the provision of data, giving help or advice about science, providing financial assistance, or offering that often well needed emotional (and sometimes alcoholic) support, they all deserve my most sincere thanks. I couldn’t possibly list everyone individually (and any attempt would read as dull as an Oscars acceptance speech) but I would like to mention some of those people who have been vital to the completion of this thesis.

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A famous philosopher once said: ‘The brain works at its best, when given time to rest’. It would therefore be criminal of me not to thank all of the friends that have helped me take time out from work to reflect, and, on occasion, get drunk too. ‘Ashfield Road’ in particular, has been a true sanctuary at times and my thanks goes to the guys there for some truly unaccountable moments. Thanks also to Andrew, James, and everyone from the undergrad’ years, especially my tutor, Agneta, without whom I would certainly not have made it this far.

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Appendix

References
The subject of space plasma physics is vast, encompassing studies of the Sun, the Earth and the other planets, and all of the 'space' in between. This thesis concerns work conducted in the field of solar-terrestrial physics, namely, the way in which the coupled system of the Earth's magnetosphere and ionosphere responds to changes in interplanetary conditions. It discusses in detail observations of plasma convection in the nightside high-latitude ionosphere, and how this relates to the controversial subject of geomagnetic tail dynamics. Details of this controversy, and the underlying physics involved are given in Chapter 2. Chapter 3 then introduces the observational facilities and techniques employed in the collection of data used in this thesis. Chapter 4 discusses ionospheric observations of the excitation of twin-vortex flow associated with the onset of an isolated magnetospheric substorm, while Chapter 5 discusses similar observations of the flows which exist under conditions of northward, but B_y-dominated IMF. Finally, Chapter 6 summarises the main findings, and discusses possible directions for ongoing and future work. Initially, however, this chapter provides some basic theory of space plasma physics, an introduction to the main components of the solar-terrestrial environment, and a brief discussion of the way in which they interact.

1.1 Theoretical Background

A space plasma is a magnetised, ionized gas which is, on average, charge neutral. In general, the behaviour of a magnetised plasma is complex, involving the mutual interaction between the charged particle assembly and the electromagnetic field via Newton's and
Maxwell’s laws. However, a first approximation to the behaviour of space plasmas can be made by considering the motion of individual particles in an electromagnetic field.

1.1.1 Frozen-in Flow

In a uniform steady magnetic induction, $\mathbf{B}$, ions and electrons (the constituents of a plasma) gyrate transverse to the field in circles about their gyrocentres with a gyrofrequency, $\Omega$. They also move with uniform speed along the field, $V_{//}$, their net motion therefore being a helix. If a uniform electric field $E$ is added perpendicular to $B$, then to this motion will be added a particle drift, $V_d$ (called the ‘$E \times B$’ drift) which is perpendicular to both $E$ and $B$, given by:

$$V_d = \frac{E \times B}{B^2}.$$  \hspace{1cm} (1.1)

This drift is independent of mass and charge, such that it is equivalent to say that imposing a drift, $V_d$, on the original system would introduce the existence of an electric field given by:

$$E = -V_d \times B.$$  \hspace{1cm} (1.2)

Now consider a more general, time-varying electromagnetic field, with $E$ again perpendicular to $B$. If a population of particles have gyrocentres which are located on one field line at one instant in time, then at any other instant in time their gyrocentres will also be located on one field line, as illustrated in Fig. 1.1. This implies that there is no relative movement between the plasma and the magnetic field, which is the principle of ‘frozen-in flow’ (e.g. Alfvén and Fälthammar, 1963; Nicholson, 1983). Substitution of Eq. 1.2 into Faraday’s law, then gives us the equation for frozen-in flow:

$$\frac{\partial \mathbf{B}}{\partial t} = \text{curl}(\mathbf{V} \times \mathbf{B}),$$  \hspace{1cm} (1.3)

where $\mathbf{V}=V_d+V_{//}$. This result is of central importance to the behaviour of space plasma systems, as we shall see below. It important to note however, that the above approximation only holds for collisionless plasmas, and fields with large spatial scales and long time
Figure 1.1 Sketch showing the motion of charged particles in a non-uniform magnetic field $\mathbf{B}$ in the presence of a perpendicular electric field $\mathbf{E}$. On the left we show some charged particles whose centres of gyration lie at some time on one field line. After a certain time they have moved due to $\mathbf{E} \times \mathbf{B}$ drift and to motion along the field. The "frozen-in" theorem then tells us that their centres of gyration still lie on one magnetic field line, as shown (from Cowley, 1993).
scales compared to the particles' gyroradius and gyropoint. Inhomogeneities in the magnetic field can introduce additional drifts (i.e. \(\text{grad } \mathbf{B}\) and curvature drift) for which the frozen-in approximation is not valid. The main perpetrator for causing a breakdown of frozen-in flow, however, are collisions which will be discussed further below.

First, however, there is a third kind of particle motion which needs to be introduced. The 'gyro' motion of particles around magnetic field lines, and the 'drift' motion in the direction of \(\mathbf{E} \times \mathbf{B}\) can also be accompanied by a 'bounce' motion. If there is a field-aligned gradient present in the field strength, the field-parallel component of a particle's velocity will decrease as it moves into a region of increasing field magnitude (the field-perpendicular component correspondingly increases to conserve the total energy). Eventually the parallel velocity reverses in a process called 'magnetic mirroring', where motion between two mirror points is called 'bounce' motion. This process is particularly relevant in planetary magnetic fields, where particles bounce rapidly along the field lines between mirror points in the northern and southern hemispheres, as will be seen below.

### 1.1.2 Collisional Effects

Space plasmas are, in the main, collisionless plasmas, i.e. ones in which the mean free path is greater than the scale size of the system. However, there are regions of space where collisions do occur and, as mentioned above, this gives rise to one of the circumstances in which the frozen-in approximation is no longer valid. Consider Fig. 1.2, which illustrates the electron and ion motion due to perpendicular magnetic and electric fields in various collisional environments. Firstly, (a) shows the collisionless case, discussed above, in which both electrons and ions move with the \(\mathbf{E} \times \mathbf{B}\) drift, and are thus frozen-in to the magnetic field. An ion (or electron) which starts at some arbitrary point (1), will feel a force \(q\mathbf{E}\), causing it to accelerate in the direction of (opposite to) the electric field. It will then feel a force \(q\mathbf{V} \times \mathbf{B}\), causing it to turn into the \(\mathbf{E} \times \mathbf{B}\) direction until at point (2) the \(q\mathbf{V} \times \mathbf{B}\) force is opposite the \(q\mathbf{E}\) force, but twice as strong. Turning therefore continues until it is moving in the direction opposite to which it started, and eventually comes to rest.
Figure 1.2 Electron and ion motion due to perpendicular electric and magnetic fields in various collisional environments (adapted from Wild, 2000).
at point (3). This cycle then repeats indefinitely. Should a particle suffer a collision, however, then this motion is interrupted and the cycle restarts before it is complete. This is illustrated, for example, in (b), in which the particle’s collision frequency, \( \nu \), is equal to its gyrofrequency. It no longer drifts purely in the \( \mathbf{E} \times \mathbf{B} \) direction, but now has a net mobility in both the \( \mathbf{E} \times \mathbf{B} \) and \( \mathbf{E} \) directions. Finally, if the collision frequency should increase such that \( \nu \gg \Omega \), then the situation illustrated in (c) arises, in which the particles have virtually no mobility in the \( \mathbf{E} \times \mathbf{B} \) direction at all and simply move slowly in the direction of the electric field.

The main effect of this relative motion between ions and electrons is to introduce currents in the plasma (the origins of which are discussed further in the context of planetary ionospheres below). This effect can be incorporated into Eq. 1.2 which then becomes:

\[
\mathbf{E} = - \mathbf{V} \times \mathbf{B} + \frac{\mathbf{j}}{\sigma},
\]

where \( \mathbf{j} \) is the electric current density and \( \sigma \) is the electrical conductivity in the plasma. Introducing this expression into Faraday’s law (and assuming uniform conductivity) gives:

\[
\frac{\partial \mathbf{B}}{\partial t} = \text{curl}(\mathbf{V} \times \mathbf{B}) + \frac{\nabla^2 \mathbf{B}}{\mu_0 \sigma},
\]

where the second term represents diffusion of the field through the plasma.

### 1.1.3 Magnetic Reconnection

An important consequence of this relative motion between the magnetic field and the plasma is a process known as ‘magnetic reconnection’, in which field lines can break and ‘re-connect’. Consider the field configuration of Fig. 1.3 (a), in which the oppositely directed field lines of two distinct plasma populations are separated by an intense current sheet (shaded grey). The fields either side of the current sheet may diffuse relative to the plasma where they are annihilated. To maintain this process in a steady state, flow must
Figure 1.3 Sketch showing the effects of magnetic reconnection between two oppositely directed field lines (solid arrowed lines) separated by an intense current sheet (grey shaded area). The large black arrows show the direction of plasma motion and the circled dot shows the direction of the electric field.
transport magnetic flux towards the boundary at the rate at which it is being annihilated. Introducing this plasma inflow, however, creates an unphysical picture since there is no means for the plasma to escape from the system. This problem is circumvented by allowing annihilation to occur over only a limited extent of the field lines. This results in the formation of an x-type configuration as shown in (b-c) with field lines which connect through the current sheet between the two plasma regimes. The magnetic tension effect (discussed below) will then cause the current sheet plasma and the reconnected field lines to contract along the current sheet away from the site of reconnection, illustrated in (d). The reconnection process is key to the interaction between different plasma populations, as will be seen below. For a more detailed description see, e.g. Kivelson and Russell (1995).

1.1.4 Magnetic Force

The reconnection process described above is one example where the electromagnetic field exerts a force on the plasma. This force is the sum of the electric force, \( qE \), and the magnetic force, \( q \mathbf{v} \times \mathbf{B} \). However, summing these forces over some finite volume of plasma gives no net electric force since the plasma as a whole is charge neutral, as mentioned previously. The total magnetic force per unit volume sums to \( \mathbf{j} \times \mathbf{B} \) and represents the effects of magnetic pressure and tension. When the magnetic pressure is greater than the plasma pressure, the magnetic force usually dominates the thermal-pressure forces, and may accelerate the plasma up to a limiting speed called the Alfvén speed, or hydromagnetic speed (Alfvén and Fälthammar, 1963), given by:

\[
V_A = \frac{B}{\sqrt{\mu_0 \rho}}, \tag{1.6}
\]

The magnetic force can be decomposed by writing:

\[
\mathbf{j} \times \mathbf{B} = (\mathbf{B} \cdot \nabla) \frac{\mathbf{B}}{\mu_0} - \nabla \left( \frac{B^2}{2\mu_0} \right). \tag{1.7}
\]
The first term on the right then represents the tension effect in the magnetic field, which gives a force when the field lines are curved. Frozen-in plasma motion in response to this force is such as to reduce the curvature of the field (exemplified, for example, in Fig. 1.3 (c) as discussed above). The second term on the right is the magnetic pressure term, and shows that the force per unit area exerted by the field on the plasma is $B^2/2\mu_0$. The concepts of magnetic tension and pressure are essential to the discussion of magnetospheric dynamics below.

1.1.5 Field–Plasma Energy Exchanges

We can also discuss the energy flow in the plasma using the reconnection process illustrated in Fig. 1.3. When the plasma is accelerated by the field it is also energised. The energy input from the field to the plasma (per unit volume per unit time) is given by $\mathbf{j} \cdot \mathbf{E}$. In a steady state, conservation of energy (Poynting’s Theorem) is then expressed as:

$$\text{div } \mathbf{S} + \mathbf{j} \cdot \mathbf{E} = 0$$  

(1.8)

where $\mathbf{S}$ is Poynting’s vector which describes the energy flux (energy per unit area per unit time) in the electromagnetic field. Thus where $\mathbf{j} \cdot \mathbf{E}$ is positive, the plasma gains energy from the field (as is the case from the field configuration in Fig. 1.3 (c)) and such a region is a sink of $\mathbf{S}$ (div $\mathbf{S}$ negative), whilst where $\mathbf{j} \cdot \mathbf{E}$ is negative the plasma loses energy to the field and such a region is a source of $\mathbf{S}$. This concept is useful in understanding plasma coupling processes which are central to the field of solar-terrestrial physics.

1.2 The Solar-Terrestrial Environment

This section introduces the main components of the solar-terrestrial environment and discusses how the theoretical aspects of space plasma physics outlined above apply to solar-terrestrial dynamics.
1.2.1 The Sun, the solar wind and the IMF

The Sun is, quite literally, of central importance to everything which we find in our solar system. Although it takes up only a small fraction of the space (the solar system extends to about 10,000 times the Sun’s radius of 696,000 km), it accounts for over 99% of the mass. It is, essentially, just a massive ball of gas held together and compressed under its own gravitational attraction. It consists principally of hydrogen and helium, which are mostly ionised due to the high temperatures experienced. Its atmosphere consists of three layers, illustrated in Fig. 1.4. The lowest of these is the photosphere, which is only 500 km thick and emits most of the Sun’s visible light. This is a relatively cool region of the Sun, where its temperature falls to \( \sim 5,800 \) K and consists mostly of unionised gas. Above the photosphere lies the rarer and more optically transparent chromosphere, the coolest region of the Sun at a mere 4,200 K. Above this region, the temperature begins to increase again, first slowly, then very quickly such that at the base of the corona the temperature is \( \sim 10^6 \) K. The gas pressure here is sufficiently high that the plasma cannot be confined by the Sun’s gravity, and instead it flows continuously outwards into the solar system to form the solar wind. The Sun also has an intrinsic magnetic field, which is transported out into the solar system frozen into the solar wind where it is termed the interplanetary magnetic field or IMF. Owing to the Sun’s rotation however, these field lines do not extend radially with the flow but are drawn into a spiral formation (Parker, 1963), now known as the Parker Spiral, which is illustrated in Fig. 1.5.

The solar wind and IMF populate the vastness of interplanetary space and are the key to the Sun’s influence on the planetary outer environments. Some typical properties of the solar wind at 1 AU (\( \sim 1.5 \times 10^8 \) km, the distance from the Sun to the orbit of the Earth) are given in Table 1.1 below. It is evident from these values that the flow speed is about an order of magnitude greater than both the sound speed and the Alfvén speed, resulting in a flow which is highly supermagnetosonic. As a consequence of this a ‘shock’ will be formed should the solar wind flow encounter an obstacle such as a planet. Most important from our point of view, however, is the magnetisation of the solar wind plasma by the IMF,
Figure 1.4 Overall structure of the solar interior and the solar atmosphere (adapted from Kivelson and Russell, 1995).

Figure 1.5 Spiral interplanetary magnetic field lines frozen into a radial solar wind expansion at 400 km s\(^{-1}\) (adapted from Parker, 1963).
Typical Properties of the Solar Wind near the Orbit of the Earth (1 AU)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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<td>Proton number density</td>
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<tr>
<td>Flow speed</td>
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<tr>
<td>Proton temperature</td>
<td>$1.2 \times 10^5 \text{ K}$</td>
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<tr>
<td>Gas (thermal) pressure</td>
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<tr>
<td>Dynamic pressure</td>
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<tr>
<td>Alfvén speed</td>
<td>$40 \text{ km s}^{-1}$</td>
</tr>
<tr>
<td>Sound speed</td>
<td>$60 \text{ km s}^{-1}$</td>
</tr>
<tr>
<td>Magnetic Field</td>
<td>$7 \text{ nT}$</td>
</tr>
</tbody>
</table>

*Table 1.1* Typical Properties of the Solar Wind near the Orbit of the Earth (1 AU)
which facilitates a dynamical interaction with planetary magnetospheres, as we shall see, below.

1.2.2 The Magnetosphere

The magnetosphere is the region of space surrounding the Earth, in which the planet’s magnetic field, generated by currents flowing in the core, is confined by the solar wind plasma. Chapman and Ferraro (1931) first deduced the concept of the magnetosphere as a closed volume based on a strict application of the frozen-in approximation. The solar wind plasma is frozen to the IMF as discussed above, and the Earth’s plasma frozen to the geomagnetic field. When these plasmas meet each other they do not mix, but instead form distinct regions separated by a thin boundary called the magnetopause. This is illustrated in Fig. 1.6, which shows a cross-section of the magnetosphere in the noon-midnight meridian. The magnetopause is usually observed at a geocentric distance of about $10 \, R_E$ on the dayside, the distance at which the magnetic pressure of the terrestrial field is equal to the dynamic pressure of the solar wind. On the nightside, however, no such simple pressure balance exists and the magnetosphere extends into a geomagnetic tail, hundreds of Earth radii long. Across the magnetopause the magnetic field usually undergoes a sharp change of strength and direction, which requires a sheet of electrical current flowing in the plasma at this interface, called the Chapman-Ferraro current. A similar current sheet exists along the centre of the geomagnetic tail for much the same reasons. A bow shock is also apparent upstream of the magnetosphere, which forms because the speed of the solar wind relative to the Earth is much faster than that of wave propagation within it (as discussed above). Across the shock the flow is slowed, compressed, and heated forming a layer of turbulent plasma outside the magnetopause called the magnetosheath.

As mentioned previously, there are circumstances where this frozen-in approximation breaks down, such as in the presence of high current densities like those found at the magnetopause. Here, the interplanetary and terrestrial field lines can reconnect in the manner discussed above. Dungey (1961) conceived the idea of an open magnetosphere
SPECIAL NOTE

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Figure 1.6 Cross section of the simplest model of the magnetosphere in the noon-midnight meridian. The arrowed solid lines show the magnetic field lines. The circled dots indicate currents out of the plane of the diagram and the circled crosses represent currents into the plane (from Kivelson and Russell, 1995).
Chapter 1  Introduction to solar-terrestrial physics

Based on this concept, in which reconnection processes both at the magnetopause and in the tail dominate the dynamics of the system. This is illustrated in Fig. 1.7, which shows the flow of plasma within the magnetosphere driven by reconnection at the subsolar magnetopause for the case where the IMF points southward (other IMF orientations are discussed in Chapter 2). The numbered field lines show the succession of configurations a geomagnetic field line (1) assumes after reconnection with an IMF field line (1'). The distended loops of 'open' magnetic flux which are formed contract over the poles and are carried downstream into the tail, where they close by further reconnection (between field lines 6 and 6'). This process forms distended closed flux tubes on one side of the tail reconnection site (e.g. field line 7), which contract back towards the Earth and eventually convect round to the dayside where the process can repeat. On the other side, disconnected field lines (e.g. field line 7') accelerate the tail plasma back into the solar wind. This cyclical flow, or 'Dungey Cycle', excited by the reconnection processes, is the key feature of the 'open' magnetosphere. It should be noted however, that the magnetosphere does not generally evolve in a steady state of convection. If, for example, the rate of reconnection at the dayside magnetopause should exceed that in the tail, the open flux being added into the tail lobes begins to build up. The system then undergoes a characteristic evolution on a 1-2 hour timescale called a magnetospheric substorm (Akasofu, 1968), involving the initial build-up of flux in the tail (the substorm growth phase), followed by an explosive release of magnetospheric energy in the tail (expansion phase). This, and other time-dependant processes are discussed in more detail in Chapter 2.

The energy flow associated with this convection process is illustrated in Fig. 1.8, which again shows a cross-section of the magnetosphere in the noon-midnight meridian. It can be seen that current flows out of the plane of the diagram in both the dayside magnetopause (Chapman-Ferraro) current sheet and in the centre plane of the tail, which are the current sheets where reconnection is occurring. These currents are in the same direction as the electric field, giving a positive $\mathbf{j} \cdot \mathbf{E}$, so that plasma is energised in these regions. However, current flows into the plane of the diagram over the tail lobe magnetopause, where the field tension effect opposes the tailward flow of the magnetosheath plasma. These currents are
Figure 1.7 Cross section of the 'open' model of the magnetosphere in the noon-midnight meridian. The arrowed solid lines show the magnetic field lines. The numbered field lines show the succession of configurations a geomagnetic field line assumes after reconnection with an IMF field line (1') at the front of the magnetosphere (from Kivelson and Russell, 1995).
Figure 1.8 Cross section of the open magnetosphere in the noon-midnight meridian plane showing the principal field-perpendicular currents and the flow of electromagnetic energy. The arrowed solid lines show the magnetic field lines, the arrowed short-dashed lines show the flow of electromagnetic energy (the Poynting flux $\mathbf{S}$), and the unlabelled circled symbols the direction of the field transverse current flow. The circled dots indicate current flow out of the plane of the diagram, and the circled crosses current flow in. The magnetopause and bow shock are indicated by the dot-dashed lines (from Cowley, 1991).
in the opposite direction to the electric field, resulting in a negative $\mathbf{j} \cdot \mathbf{E}$, so here the plasma loses energy to the field. The energy extracted from the magnetosheath plasma flows into the tail lobes as a Poynting flux, and is then fed into the plasma in the centre of the tail. This is the dominant energy exchange process which powers convection-dominated magnetospheres such as the Earth's.

As well as being the dominant mechanism by which energy and momentum are transferred, reconnection also facilitates the entry of plasma from the solar wind into the magnetosphere. The solar wind is one of two sources of magnetospheric plasma, whose different populations are illustrated in Fig. 1.9. The magnetosheath, mentioned above, the boundary layer, which lies on open field lines adjacent to the dayside magnetopause, and the plasma mantle of the outer tail lobes, are all primarily composed of solar wind plasma. Plasma which flows into the central current sheet forms a second population called the plasma sheet (this population consists roughly equally of solar wind and ionospheric plasma, discussed below). This plasma (termed 'hot' owing to the energy input described above) is accelerated back into the solar wind down-tail of the reconnection region, and towards the Earth on the Earthward side. The Earthward directed plasma then finds itself on closed field lines causing it to mirror near the Earth and return to the current sheet. There it will be further accelerated followed by a second mirroring on the opposite side of the current sheet, and thus become trapped in the 'bounce' motion described above. Owing to the Earthward contraction of the closed field lines during a plasma particle's time of flight, mirrored particles will only exist in a region well Earthward of the original acceleration region. Purely Earthward directed plasma is therefore only found tailward of the return flux of particles mirrored from the Earth, and as such it is confined to the outer surface layer of the plasma sheet called the plasma sheet boundary layer (PSBL). It was mentioned above that ionospheric plasma (plasma from the Earth's upper atmosphere), a second source of plasma in the magnetosphere, also contributes to the plasma sheet population. In fact, ionospheric plasma can be found in the boundary layer, plasma mantle and magnetosheath in small amounts. The main magnetospheric population of ionospheric plasma however, is the plasmasphere and polar wind. The plasmasphere is composed of
Figure 1.9 Cross section of the 'open' model of the magnetosphere in the noon-midnight meridian showing the different magnetospheric plasma populations.
high density cold ionospheric plasma contained in a central core of dipolar flux tubes which corotates with the Earth. However, outside of this core at higher latitudes the ionospheric plasma is not contained and therefore flows continuously outwards in an attempt to ‘fill’ the open flux tubes. This outflow, similar in principle to the outflow of solar plasma into the solar system, is called the ‘polar wind’.

1.2.3 The Ionosphere

Beneath the magnetosphere is the Earth’s upper atmosphere. Above an altitude of ~60 km the characteristics of the atmosphere are governed by the action and absorption of solar far-UV and X-radiation. The most important of these actions, for our purposes, is the partial ionisation of the neutral atmosphere and formation of the ionosphere. Fig. 1.10 shows a typical altitude profile of (a) the atmospheric temperature and (b) the ionospheric plasma density. It is evident from a comparison of these two figures, that the ionosphere exists primarily within the mesosphere and thermosphere. Although only weakly ionised (the ionosphere contributes less than 0.1% to the total thermospheric density), it is this attribute which facilitates coupling to the magnetosphere and hence controls the dynamics of the upper atmosphere. Three principal regions of the ionosphere are identified (termed D, E and F, as indicated on Fig. 1.10 (b)), which are classified in terms of ionic species. The D region, which lies between about 60 and 90 km is characterised by the presence of complex photochemical reactions, NO, water cluster ions, and the presence of negative ions rather than electrons. The E and F region plasmas, which are of particular importance to the work of this thesis, are discussed in more detail below.

The E region, which lies between 90 and 150 km, is dominated by molecular ions, NO+ and O2+, and it is in this region that the ionospheric currents which couple to the magnetosphere originate. These currents are due to a relative drift between ions and electrons, which arises because of collisions between ions and the neutral atmosphere. This relative drift is illustrated on the left-hand side of Fig. 1.11 by the blue arrows, which show the direction (and relative magnitude) of the ion and electron motion with respect to the E and
Figure 1.10 Typical profiles of neutral atmospheric temperature and ionospheric plasma density (day and night) (from Kelly, 1989).
Figure 1.11 An altitude profile of the ionosphere showing the relative drifts of ions and electrons (left-hand side) and the corresponding Hall and Pedersen conductivities ($\sigma_H$ and $\sigma_P$, respectively) and electron number density, $n$, (right-hand side). The blue arrows show the net horizontal particle drift with respect to $E$ and $E \times B$ assuming a vertical field.
The $\mathbf{E} \times \mathbf{B}$ directions. At the base of the E region, the ion-neutral collision frequency, $\nu_m$, is so high that the ions are effectively motionless with respect to the neutral atmosphere, as illustrated. The electrons on the other hand, $\mathbf{E} \times \mathbf{B}$ drift throughout the E region, since their collision frequency is small compared with their gyrofrequency. The net effect of this is to cause a current in the direction opposite to $\mathbf{E} \times \mathbf{B}$ termed the Hall current. This is illustrated by the green curve on the right-hand side of Fig. 1.11, which shows the Hall conductivity, $\sigma_H$. Moving up in altitude, the neutral density (and hence $\nu_m$) decreases, and as a consequence the ions begin to have mobility in the direction of the electric field. This introduces a current flow along $\mathbf{E}$ termed the Pedersen current (the corresponding Pedersen conductivity, $\sigma_P$, is shown by the red curve in Fig. 1.11) which peaks at an altitude of $\sim 125$ km. At this altitude ion mobility in the $\mathbf{E} \times \mathbf{B}$ direction is equal to that in the direction of $\mathbf{E}$, such that the Hall and Pedersen conductivities are also approximately equal. Moving further up in altitude, increasing ion motion in the $\mathbf{E} \times \mathbf{B}$ direction causes the Hall current to decrease such that it is the Pedersen current which dominates above $\sim 125$ km. Although the Pedersen and Hall currents therefore vary with altitude, for our purposes we are only really interested in the total current integrated with height through the ionosphere. The height-integrated current components are then $\mathbf{J}_p = \Sigma_P \mathbf{E}$ and $\mathbf{J}_H = \Sigma_H \mathbf{b} \times \mathbf{E}$, where $\Sigma_P$ and $\Sigma_H$ are the height-integrated Pedersen and Hall conductivities respectively, and $\mathbf{b}$ is the unit vector along the magnetic field. The horizontal pattern of these currents in the ionosphere is discussed in more detail below.

Above 150 km is the F region in which $O^+$ ions are the dominant species. Collisional effects here are negligible (as mentioned above) and so the plasma simply obeys the frozen-in approximation. This results in the magnetospheric convection (discussed above) being communicated to the ionosphere where it drives flow. This flow is also discussed in more detail below.
1.2.4 Magnetosphere-Ionosphere Coupling

Certain aspects of magnetosphere-ionosphere coupling have already been introduced, such as the ionosphere forming a spatially structured source of plasma for the magnetosphere. A further aspect of magnetosphere-ionosphere coupling is the precipitation of structured magnetospheric plasma into the atmosphere. At different latitudes, different adjacent regions of the magnetosphere give rise to different plasma precipitation zones, illustrated in Fig. 1.12 (a), which shows a view of the high-latitude ionosphere looking down onto the north pole of the Earth. At lower latitudes, the plasma maps along the magnetospheric field lines into the plasmasphere, and consequently there is little energetic particle precipitation in this region under usual conditions. At higher latitudes is the region which maps to the plasma sheet. Precipitation into this region enhances ionisation and results in the production of diffuse ‘aurora’ by electronic excitation followed by photoemission. Poleward of this is the region mapping to the boundary layer and dayside cusp. The cusp is the dayside region where recently reconnected field lines accelerate magnetosheath plasma into the ionosphere. This process can also produce auroral emissions and, together with the plasma sheet, this region forms the circumpolar auroral zone. Lastly, the region known as the polar cap which lies at the highest latitudes maps to the tail lobe and plasma mantle. Here, precipitation of weak, structureless magnetosheath particles called polar rain produces little auroral luminosity, so the central region of open field lines is optically dark.

The other major impact which the magnetosphere has on the ionosphere is the communication of convection processes mentioned previously. Fig. 1.12 (a) also shows the ionospheric image of the magnetospheric plasma flow, indicated by the solid arrowed streamlines. The flow consists of twin vortices with open field lines that flow away from the Sun over the polar caps and closed field lines that flow back towards the Sun at lower latitudes. The dashed circle at the reversal of these streamlines represents the boundary between open and closed field lines. On the outer streamline of the dusk vortex are marked the positions of the feet of the numbered field lines in Fig. 1.7, illustrating how the ionospheric convection pattern is related to the flow in the magnetosphere. This flow,
Figure 1.12 View looking down on the northern high-latitude ionosphere showing the plasma $E \times B$ drift paths (arrowed solid lines) and (a) the main magnetospheric plasma precipitation zones, (b) the main ionospheric current systems. The interior heavy dashed circle in each sketch shows the boundary between open field lines at high latitudes and closed field lines at lower latitudes. In (b) the arrowed short-dashed lines show the ionospheric Pedersen current along $E$, while the circled dots and crosses show the upward and downward directed closure field-aligned currents respectively (after Cowley, 1993).
However, is opposed by the ion-neutral collisions at E region heights mentioned above, and is maintained against this neutral drag via a large scale current system imposed by the magnetosphere.

Fig. 1.12 (b) shows the overall pattern of ionospheric currents in a view of the northern ionosphere similar to that in Fig. 1.12 (a). Since the Hall currents flow in the direction opposite to the $E \times B$ drift, the plasma flow streamlines also represent the pattern of the Hall current flow, in the direction opposite to the arrows shown. Although in principle these Hall currents could close wholly in the ionosphere, the non-uniformity of the ionospheric conductivity results in discontinuities in the Hall current. These are manifest as, for example, eastward and westward 'electrojet' currents, which require closure in the magnetosphere via magnetic field-aligned currents (FAC) flowing into and out of the auroral zones. These electrojets, and their associated magnetic signatures are discussed further in Chapter 2. The arrowed short dashed lines in Fig. 1.12 (b) show the electric field lines associated with the flow, and hence also the pattern of Pedersen currents. These currents flow from dawn to dusk across the polar cap, reversing in sense in the auroral zone. It is clear that these currents cannot close in the ionosphere, but must close in the magnetosphere via a system of field-aligned currents. These FAC are indicated on Fig. 1.12 (b) by the circled dots (upward FAC) and circled crosses (downward FAC). The inner (higher latitude) system of FAC is termed 'Region 1', and the outer (lower latitude) system 'Region 2'. These extended sheets of FAC produce magnetic perturbations which are aligned with the plasma flow. However, the sum of the FAC and the Pedersen current gives no net magnetic perturbation underneath the ionosphere, if the ionosphere is uniformly conducting and the magnetic field is vertical. Although this will not generally be perfectly true, it is reasonable to assume on this basis that observed magnetic perturbations on the ground will therefore be mostly due to Hall currents, an assumption which is key to some of the work in this thesis.
The physics behind the closure of these currents in the magnetosphere can be thought of in terms of simple circuit theory, in which a generator (the flowing solar wind or magnetospheric plasma) is connected across a load (caused by frictional drag in the ionosphere) by currents flowing along highly conducting wires (the FAC). The Pedersen current flows from dawn to dusk in the polar cap, up the dusk Region 1 FAC to the magnetopause where it closes from dusk to dawn, and then back down into the ionosphere in the dawn Region 1 FAC. The magnetosheath plasma loses energy to the field (\( j \cdot E \) is negative in the magnetopause), the ionospheric plasma gains energy from the field via Joule heating (\( j \cdot E \) is positive in the Pedersen current) and electromagnetic energy flows from the former region to the latter in the space between them as a Poynting flux. A more complex current circuit is associated with the Region 2 FAC, involving closure within the inner plasma sheet. One further consequence of, specifically, the upward directed FAC, is the formation of discrete auroral forms. These are particularly prominent in the dusk flow reversal region where Region 1 current flows upward out of the ionosphere, carried by precipitating hot magnetospheric electrons which are accelerated downwards by field aligned voltages.

The most important feature of the magnetosphere-ionosphere flow system is that its strength is modulated by variations in the direction and strength of the IMF. The dayside reconnection rate, and hence the magnetic flux throughput in the magnetosphere, is strong when the IMF points south, opposite to the equatorial field of the Earth. When the IMF points north, equatorial reconnection cannot occur, and the cyclical flow described above dies away. A quantity often used as a measure of the size of the flows is the total transpolar voltage, \( V_{PC} \). Since the ionospheric electric field is essentially curl free (due to the strength and incompressibility of the ionospheric magnetic field), it can be described by the gradient of a scalar potential. The flow streamlines in Fig. 1.12 therefore also represent equipotentials, and \( V_{PC} \) is then defined as the difference between the maximum of the electric potential (at the focus of the dawn flow cell) and the minimum (at the focus of the dusk flow cell). 1 volt is then equivalent to the transport of 1 Wb s\(^{-1}\) of flux across a line joining these two foci, with typical values of \(~50\) kV being observed. A more detailed
description of ionospheric convection under various orientations of the IMF is given in Chapter 2. However, exactly how the convection pattern responds to changes in the IMF, particularly in the nightside ionosphere, is still unresolved. The work discussed in Chapters 4 and 5 of this thesis provides evidence of the nightside flows which occur in the ionosphere under various IMF conditions, and thus brings us closer to a unified concept of magnetospheric-ionospheric convection.
Plasma flow in any coupled magnetosphere-ionosphere system is governed by two independent processes. The first is corotation, in which the plasma and magnetic field rotate with the angular velocity of the planet, and the second is solar wind-driven convection. Generally, corotation dominates at smaller radial distances from the planet and solar wind-driving dominates at larger distances. For some planets, such as Jupiter, the distance at which this dominancy switches is large, such that corotation dominates over essentially the entire magnetosphere. In the case of the Earth’s magnetosphere however, corotation is only important up to a few Earth radii from the planet, resulting in the small ‘plasmashere’ of corotating flux. Elsewhere in the magnetosphere the dynamics are governed by interactions with the solar wind and interplanetary magnetic field. It is the aim of this chapter to give a general review of magnetospheric-ionospheric convection and associated phenomena in terms of the driving mechanisms employed by the solar wind.

2.1 Steady state convection

The principal physical process involved in the driving of convection in the magnetosphere-ionosphere system by the solar wind is magnetic reconnection (Dungey, 1961). In the simple picture of Dungey cycle convection given in Chapter 1, reconnection occurs at two locations. The first of these is the dayside magnetopause between closed geomagnetic field lines and the IMF, and the second is between the open magnetic flux of the tail lobes. Convection can also be driven by reconnection between the IMF and pre-existing open tail lobe flux, which does not contribute to the Dungey cycle as such, but causes ‘circulation’ of
open flux in the tail lobes and polar cap (Dungey, 1963). Non-reconnection or 'viscous' coupling processes may also contribute at modest levels (e.g. Farrugia et al., 2001).

The exact nature of the solar wind driving is largely influenced by the orientation of the interplanetary magnetic field, which controls where on the magnetopause reconnection occurs and the nature of the forces on the open flux tubes downstream of the reconnection site. More precisely, it depends primarily on the strength and orientation of the transverse GSM $y$ and $z$ components of the field, whose direction is given by the 'clock angle', $\theta$, with respect to north. Thus $0^\circ$ clock angle corresponds to a transverse field purely in the $+z$ direction (northward), $\pm 90^\circ$ to $\pm y$ (respectively), and $\pm 180^\circ$ to $-z$ (southward). In general, the nature of the reconnection which occurs, and that of the convection which follows from it, are thus classified in terms of IMF orientation, as will be discussed below.

2.1.1 Southward IMF and the $B_z$-asymmetry

When the interplanetary field points south, the dynamics of the system are governed by Dungey-cycle flow and the substorm cycle (Dungey, 1961; Hones, 1979; Farrugia et al., 1993; Baker et al., 1996). The excitation of flow in the dayside ionosphere during intervals of southward IMF and associated magnetopause reconnection is now a well-established phenomenon (e.g. Etemadi et al., 1988; Todd et al., 1988; Ruohoniemi et al., 1993; Khan and Cowley, 1999). Even the substructure of characteristically pulsed dayside reconnection (i.e. 'flux transfer events', discussed below) are well-resolved in dayside flow and auroral data as 'pulsed ionospheric flows' (Lockwood et al., 1989, 1993; Elphic et al., 1990; Pinnock et al., 1993, 1995; Provan et al., 1998; Milan et al., 2000; Wild et al., 2001). As a consequence, there is now little uncertainty about the central role of magnetopause reconnection in magnetospheric dynamics and flow excitation.

For extended intervals of steady, balanced, dayside and nightside reconnection, the expected ionospheric convection patterns in the northern hemisphere are those illustrated in Fig. 2.1. The top centre panel shows the case for a purely southward IMF corresponding to
Figure 2.1 Sketch showing the form of the high-latitude ionospheric flows in the northern hemisphere for differing orientations of the interplanetary magnetic field (after Lockwood, 1991).
Chapter 2  Coupled magnetospheric–ionospheric convection

the simple Dungey-cycle convection introduced in Chapter 1. The top right and left panels then show the effects of introducing a positive or negative $B_y$ component to the IMF, respectively. The asymmetry in the flow patterns is a result of the altered geometry of the reconnecting field lines, as shown in Fig. 2.2. Reconnection now produces field lines which no longer convect in a purely anti-sunward direction, but are instead pulled towards dusk and dawn by the field tension effect (Jørgensen et al., 1972; Cowley, 1981). This adds a zonal flow to the field lines as they convect antisunward over the polar cap which, in the ionosphere, produces the ‘banana and orange’ twin flow cells as shown.

The departure of the IMF from a purely southward orientation also tends to change the location of the reconnection site on the magnetopause (Crooker, 1979). This supports the idea that anti-parallel fields are favoured for reconnection to occur. An alternate hypothesis is that of component merging, in which reconnection can occur for any non-parallel fields. This would likely result in the reconnection site remaining close to the subsolar region where the magnetosheath flow is slow and the static plasma pressure is high (Sonnerup, 1974; Gonzales and Mozer, 1974). In fact, therefore, magnetopause reconnection may well involve elements of both, although no definitive model yet exists. For a recent discussion of the implications for anti-parallel and component reconnection see Lockwood et al. (2002). Fig. 2.3 illustrates the location of the reconnection site based on the anti-parallel assumption to give an indication of the likely locations of reconnection and how they depend on the IMF. Fig. 2.3a shows an example IMF (blue arrowed lines) and the location of potential reconnection lines on the magnetopause where the IMF and geomagnetic field are anti-parallel (thick red curve). Fig. 2.3b shows the potential reconnection lines for a variety of IMF orientations, colour coded according to the different IMF directions in the $y$-$z$ plane indicated on the inset. As the IMF vector sweeps from southwards to northwards through positive $B_y$, the reconnection site moves polewards, and is displaced towards dusk in the northern hemisphere and dawn in the southern hemisphere, as indicated in Fig. 2.3b (for negative $B_y$ this asymmetry is reversed in sense). It is therefore clear that the location of the reconnection site will often be far from the nose of the magnetosphere as was implied by the simple case of purely southward IMF discussed in Chapter 1.
Figure 2.2 Configuration of newly reconnected field lines for the cases when the IMF is southward and has (a) a positive $B_y$ component and (b) a negative $B_y$ component, viewed from the Sun. The short broad arrows show the direction that magnetic tension will tend to pull the field lines (adapted from Gosling et al., 1990).
Figure 2.3 Cartoons of the front of the magnetosphere illustrating the location and geometry of antiparallel reconnection (or merging) between geomagnetic field lines (black arrowed lines) and the IMF. (a) shows an example IMF (blue arrowed lines) and the potential reconnection lines on the magnetopause where the IMF and geomagnetic field are antiparallel (thick red curve). (b) shows the potential reconnection lines for a variety of IMF orientations, colour coded according to the different IMF directions in the y-z plane indicated on the inset (adapted from Crooker, 1979).
2.1.2 Northward IMF and lobe reconnection

It is well established that when the interplanetary field points north, Dungey-cycle flow and substorm activity are reduced (e.g. Fairfield and Cahill, 1966; Reiff et al., 1981). At the same time, high-latitude reconnection between open lobe field lines and the IMF begins, as implied by Fig. 2.3b in the case where the reconnection site moves poleward of the cusp. This lobe reconnection is illustrated in Fig. 2.4, which shows two views of the magnetosphere in the noon-midnight meridian. In (a) the case for an intermediate clock angle is shown, such that the IMF is northward, but still with a significant By component. The numbers 1-5 show the succession of configurations a geomagnetic field line assumes after reconnection with an IMF field line (1') on the northern lobe of the magnetosphere. This ‘single-lobe’ reconnection, involving reconnection in just one hemisphere, excites IMF By-dependent convection cells within the polar cap but does not change the amount of open flux present (e.g. Reiff and Burch, 1985). The ionospheric images of this are shown in the bottom left and right panels of Fig. 2.1. Fig. 2.4 (b) shows the case for near-north orientations of the IMF, in which ‘two-lobe’ reconnection in both northern and southern hemispheres closes open flux and excites ‘reversed’ twin-vortex convection cells (e.g. Dungey, 1963; Russell, 1972; Sandholt et al., 1999, 2000, 2001), as depicted in the bottom centre panel of Fig. 2.1.

2.1.3 Non-reconnection driven flows

The cartoons of Fig. 2.1 also suggest that some Dungey-type convection may prevail for the Bz positive cases. Indeed, observations in the dayside ionosphere suggest that open flux tube production only switches off entirely if the clock angle falls below ~30°-40° (e.g. Sandholt et al., 1998a,b). Under such circumstances ‘viscous’ coupling processes may also contribute at a significant level, with peak voltages of perhaps ~10 kV. By comparison, during intervals of southward IMF and active reconnection, Dungey-cycle convection can excite voltages well in excess of 100 kV (e.g. Cowley, 1984). It is therefore reasonable to suggest that viscous driven flows are only significant during intervals of little or no
Figure 2.4 Cross sections of the Earth's magnetosphere in the noon-midnight meridian for the case (a) IMF $B_z > 0$ nT, $|B_y| > 0$ nT and (b) IMF $B_z > 0$ nT, $B_y = 0$ nT. The arrowed solid lines show the magnetic field lines. The numbered field lines in (a) show the succession of configurations a geomagnetic field line assumes after reconnection with an IMF field line ($1'$) on the northern lobe of the magnetosphere.
magnetopause reconnection, such as during intervals of strict northward IMF. In particular, if the total transpolar voltage is small, then it is more likely to be influenced by the presence of any of these non-reconnection coupling effects.

2.2 Time dependent convection

The description of Dungey cycle convection given above, and in Chapter 1, implies a steady state situation, with flux being opened at the magnetopause and closed in the tail at equal rates. Whilst these rates may well be equal when averaged over many hours, they are not necessarily equal on shorter timescales. According to the theoretical picture proposed by Cowley and Lockwood (1992, 1996), Dungey-cycle flow may be considered to be excited principally by two essentially independent processes. The first is reconnection at the magnetopause between the Earth’s field and the interplanetary field in the magnetosheath, which results in the transfer of newly-formed open flux tubes from the dayside into the tail lobes. This process causes a departure of the system from equilibrium, and excites flow which carries the system towards a new equilibrium configuration with the changed (increased) amount of open flux. In the ionosphere, the flow is of twin-vortex form, with antisunward flow over the polar cap and sunward (return) flow at lower latitudes. However, the flow is expected to be strongest on the dayside, with the ‘foci’ of the twin-vortex flow located at either end of the dayside ‘merging gap’, and is associated with an expansion in size of the open polar cap and surrounding auroral zone (Fig. 2.5a).

The second process is the reconnection of open tail lobe flux across the tail current sheet, which results in the destruction of open lobe flux, and the contraction of newly-formed closed flux tubes towards the Earth. This process similarly perturbs the system from equilibrium, and will also excite flow which is of twin-vortex form in the ionosphere. Now, however, the flow is expected to be strongest on the nightside, with the ‘foci’ of the twin-vortex flow located at either end of the nightside ‘merging gap’, and is associated with a contraction of the open polar cap and surrounding auroral zone (Fig. 2.5b). This two-
Figure 2.5 Sketch illustrating the form of the two basic time-dependent components of the high-latitude ionospheric flow due to (a) unbalanced dayside reconnection and (b) unbalanced tail reconnection. The instantaneous open-closed field line boundary is indicated by the solid oval which expands outwards in (a) while contracting inwards in (b), as indicated by the large arrows. The dashed portion of the boundary represents the merging gap mapping to the reconnection line where flow crosses the boundary between open and closed flux. In each case, the action of the flow (indicated by the arrowed streamlines) is such as to take the boundary to a new equilibrium position, shown by the dot-dashed circle (from Cowley et al., 1998).
component flow picture, while first being presented in the above form by Cowley and Lockwood (1992), is related to earlier ideas on boundary motions and flows presented by Siscoe and Huang (1985) and Freeman and Southwood (1988). The primary magnetospheric processes which are associated with these essentially independent flow components are discussed in more detail below.

2.2.1 Flux transfer events

One important cause of time dependency in the flow, as discussed above, is variations in the strength and direction of the IMF which modulates the dayside reconnection rate, combined with the finite time for communication between the dayside and nightside reconnection sites (~20 mins). However, observations show that there is also a natural time-dependence in the reconnection process itself (e.g. Lockwood and Wild, 1993). Magnetopause reconnection, for example, is observed to be an impulsive phenomenon, rather than occurring as a continuous process. Originally identified by Russell and Elphic (1978) as bipolar signatures in the component of the magnetic field normal to the magnetopause, discrete ‘flux transfer events’ (FTEs) recur with an average timescale of 5-10 minutes. Fig. 2.6a shows exemplar magnetometer data which contains a number of FTE signatures of this form. Fig. 2.6b shows a sketch of Russell and Elphic’s original interpretation of these signatures. In this sketch two open flux tubes, which exist as a result of a burst of reconnection near the nose of the magnetosphere, lie along the magnetopause partially inside and partially outside of the current sheet. The passage of either flux tube past a spacecraft therefore produces the characteristic magnetic signature which is positive then negative in the boundary normal direction for a spacecraft north of the magnetic equator, and of opposite polarity for one south of the equator. Fig. 2.7 shows the distribution of FTEs over the dayside magnetopause projected onto the GSM y-z (top) and y-x (bottom) planes. These data, taken from a survey of flux transfer events observed with the ISEE 1 spacecraft (Kawano and Russell, 1996), are consistent with the range of reconnection sites depicted in Fig. 2.3b. The nature of the convection which is then excited as a result of this reconnection is illustrated in Fig. 2.8. In this model, an FTE adds a
Figure 2.6 (a) ISEE 1 magnetic field data containing four FTE signatures (vertical dashed lines), identified by the bipolar signatures in the BN (magnetopause-normal) component of the magnetic field. The vertical dotted line indicates the time of a magnetopause crossing (from Kawano and Russell, 1996). (b) A sketch of Russell and Elphic's original interpretation of an FTE (adapted from Sonnerup, 1984).
Figure 2.7 Positions of magnetospheric FTEs (crosses) and magnetosheath FTEs (circles) in GSM (top) Y-Z plane and (bottom) Y-X plane (from Kawano and Russell, 1996).
Figure 2.8 A schematic diagram illustrating a model of the ionospheric flow response to the addition of a region of new open flux to the front of the polar cap by a flux transfer event for IMF Bz < 0 nT and By > 0 nT. Light grey shading indicates the location of the main auroral oval on closed field lines and dark grey shading indicates the region of newly opened flux. Circled dots and crosses represent upward and downward field-aligned currents, respectively. Flow streamlines are indicated by curved arrows (adapted from Milan et al., 2000).
region of open flux to the front of the polar cap and this newly opened flux is then redistributed around the polar cap boundary by the excitation of flow. However, Milan et al. (2000) suggest that the FTE is not an isolated pulse of reconnection, but an ongoing event which propagates along an expanding X-line, effectively 'peeling' off flux from the dayside magnetosphere. In the ionosphere, this is observed as an expansion of the merging gap around the polar cap boundary as shown in the figure.

2.2.2 Magnetospheric substorms

It is not just dayside reconnection which exhibits time-dependency. It has long been supposed that the major episodes of reconnection and open flux destruction in the tail take place during magnetospheric substorms (Hones, 1979; Baker et al., 1996). Introduced briefly in Chapter 1, substorms are a large-scale magnetospheric and ionospheric phenomenon involving the explosive release of magnetospheric energy which builds up as a result of the solar wind driving mechanisms discussed above. The expected relationship between tail reconnection and flow outlined above, which has recently been discussed in detail by Cowley et al. (1998) and Lu et al. (2002), is less clear than that observed for dayside reconnection. The work presented in Chapter 4 of this thesis attempts to elucidate this subject, by making a detailed analysis of the flows which are excited in association with an isolated substorm. Given below is a brief summary of current understanding on substorm phenomenology which is pertinent to the discussion in Chapter 4.

2.3 Substorm phenomenology

The substorm process involves three phases (growth, expansion, and recovery), which together make up what is known as the substorm cycle. This is, essentially, just a time-dependent form of the Dungey cycle, in which a 1-2 hour characteristic evolution of the magnetosphere takes place involving the storage (growth phase) and release (expansive phase) of magnetic energy in the geomagnetic tail. Substorms were originally discovered
nearly 40 years ago, although at first they were very much just an observational phenomenon, with much of the physics behind them not being realised for many years.

2.3.1 Phases of a substorm

The growth phase of a magnetospheric substorm essentially corresponds to an interval in which the dayside reconnection rate exceeds the nightside reconnection rate for a significant time. This predominantly occurs under conditions of southward IMF, and gives rise to the time-dependent dayside-dominated convection described above, in which flux is opened at the dayside magnetopause and added into the tail lobes. This situation is shown schematically in Fig. 2.9, which shows the changes in magnetospheric configuration associated with the substorm growth phase. The dayside magnetopause gets eroded inwards (up to an Earth radius), and the tail magnetopause moves outwards. This additional open magnetic flux represents an energy source and the ‘pile up’ of open flux squeezes the plasma sheet between the magnetotail lobes. This results in the intensification and thinning of the cross tail current which flows across the centre of the plasma sheet. Ultimately, the result of this ‘growth’ is to produce an instability in the tail which responds by undergoing a massive reconfiguration and releasing the magnetic energy which was previously stored.

At the onset of the expansive phase the tail magnetic field collapses, accelerating plasma earthwards. An impulsive perturbation associated with this dipolarisation moves through to the inner magnetosphere in the form of an Ultra Low Frequency (ULF) wave called a Pi2 pulsation, which has a period between ~ 50 and 150 seconds (Baumjohann and Glasmeier, 1984). This results in a ‘ringing’ of the magnetic field lines of the inner plasma sheet and plasmasphere, which can be seen in ground magnetometer data and is often used to time the onset of the substorm. Coincident with the field collapse is a diversion of the cross-tail current along magnetic field lines into the auroral ionosphere. This results in the formation of what is called the substorm current wedge (McPherron et al., 1973), which is illustrated schematically in Fig. 2.10. The resulting closure of this current in the ionosphere causes an
Figure 2.9 Schematic illustration of the changes in magnetic field and plasma sheet expected in the situation where the reconnection rate on the dayside exceeds that on the nightside. Increased magnetopause flaring, plasma sheet thinning, and earthward motion of the tail current are the main effects. This is the growth phase of a substorm (from Kivelson and Russell, 1995).
Figure 2.10 Schematic illustration of the three-dimensional current system that is responsible for the DP-1 current system during the expansion phase of a substorm. This illustrates the diversion of the cross-tail current through the midnight ionosphere in the formation of the substorm current wedge (from Clauer and McPherron, 1974).
intense polar magnetic disturbance on the ground. This is illustrated in Fig. 2.11b which shows the patterns of equivalent ionospheric currents which would give rise to the observed magnetic perturbations. This is called the DP-1 current system, and the enhanced westward current across the midnight sector is known as the substorm electrojet. This electrojet is observed on the ground as a large reduction in the northward horizontal magnetic field, and is termed a geomagnetic bay. For comparison, the two-cell DP-2 current system shown in Fig. 2.11a is the traditional twin-cell pattern associated with solar wind driven convection, and as such the DP-2 currents are also known as the convection electrojets.

The other main ground signature of substorms is the auroral brightening, which occurs as a result of the influx of particles accelerated earthwards from the tail. This was first recognised by Akasofu (1964) using arrays of all-sky cameras distributed around the auroral oval. A schematic representation of six stages in the development of an auroral substorm is shown in Fig. 2.12. Activity begins from a quiet state consisting of multiple arcs drifting equatorward (panel A). The ‘onset’ of the auroral substorm is then a sudden brightening of the most equatorward arc in the premidnight sector (panel B), which rapidly expands poleward and westward (panel C) forming a bright ‘bulge’ of auroral disturbance. This bulge forms a sharp kink at its westward edge which is often observed to move in a westward direction and is hence known as the ‘westward-traveling surge’ (panel D). Also depicted in this panel are the ‘omega bands’, so called owing to the shape of their poleward border, which form at the eastward edge of the bulge. The interval described, during which the auroral disturbance is observed to be expanding (i.e. panels B-D), is therefore called the ‘expansion phase’ of the substorm which usually ceases after about 30-50 minutes (panel E). Over the next ~90 minutes auroral activity dims and quiet arcs begin to reappear (panel F) in what is called the ‘recovery phase’ of the substorm. During this interval, the magnetosphere relaxes back to its pre-substorm state, responding and adjusting to the input of magnetic flux and hot plasma on the nightside during the expansion phase.
Figure 2.11 Patterns of ionospheric currents during magnetic disturbance. Closed contours shows the flow lines for an equivalent ionospheric current that produces the observed ground magnetic perturbations. (a) The two cell DP-2 current system present during the substorm growth phase. (b) The single cell DP-1 current system that dominates during the substorm expansion phase (from Clauer and Kamide, 1985).
Figure 2.12 Schematic representation of six stages in the development of an auroral substorm, as determined from all-sky camera data during the International Geophysical Year (1957) (from Akasofu, 1964).
2.3.2 Phenomenological models of substorm expansion phase onset

Although the main observational features of a substorm have been well observed, controversy still surrounds the sequence of events which occur during the few-minute phase which initiates substorm expansion. Some observations suggest that tail reconnection is initiated by near-Earth current sheet disruption followed by tailward-propagating inward collapse of the field lines (e.g. Lui, 1991, 1996; Frank and Sigwarth, 2000; Friedrich et al., 2001). However, recent results from the Geotail spacecraft show that reconnection typically begins in the dusk sector plasma sheet at down-tail distances of ~20-30 R_E a few minutes before the onset of expansion signatures on the ground (Nagai et al., 1998; Machida et al., 1999). A number of different phenomenological models have been developed over the past few decades which attempt to explain all of the observed phenomena. The two main contenders, which address the issues introduced above, are discussed in more detail below.

Probably the best developed is the near-Earth neutral line (NENL) model (McPherron et al., 1973), in which substorm onset is initiated by the formation of a new, near-Earth reconnection site about 20-30 R_E down-tail. Hones (1984) presented a detailed schematic interpretation of IMP-8 data which describes the evolution of the plasma sheet during substorm expansion. This is shown in Fig. 2.13, where midnight meridian plane cross-sections of the plasma sheet are shown at several sequential times (a dot represents the IMP-8 location at 32 R_E from earth). A neutral line (or X-line), N', forms in the near-Earth sector of the plasma sheet at substorm onset (panel 2), and subsequent magnetic reconnection causes the fast jetting of plasma earthward and tailward. The earthward jetting plasma flows along field lines to the ionosphere where it creates the auroras, as discussed above. The reconnection, continuing in panels 3 and 4, creates a structure of closed magnetic loops, and in panel 5 the last closed field line of the pre-substorm plasma sheet is pinched off by reconnection, leaving the plasma sheet tailward of N' magnetically detached from earth. Panels 6 to 8 show this detached plasma sheet, now a free 'plasmoid', being accelerating tailward by the magnetic tension imposed by lobe field lines (lines 6 and 7) which reconnected after its detachment and are contracting tailward. Panel 9 shows a very
Figure 2.13  Schematic representation of the evolution of the magnetotail in the noon-midnight meridian plane during the expansion phase of a magnetospheric substorm. Magnetic field lines are represented by black lines and plasma flows by white arrows. The location of the distant neutral line is indicated by the letter N, and that of the near-Earth neutral line by N'. The shaded area represents the plasma sheet which contains field lines 1, 2, 3, and 4, and is bounded by the last closed field line, 5. Field lines 6 and 7 are in the lobe, outside the plasma sheet (from Hones, 1984).
thin plasma sheet, downstream from the substorm X-line, which has remained at the near-Earth location of its initial formation. In this thin downstream plasma sheet one expects to find plasma flowing tailward from the X-line, threaded with open field lines having a southward orientation where they cross the midplane. Lastly, panel 10 shows the X-line, N', at a new distant location N'', and the plasma sheet of closed field lines thickening earthward of N''.

In the NENL model it is therefore reconnection which is the fundamental process resulting in the disruption of the inner tail, leading to the formation of the substorm current wedge. Further details of a proposed mechanism by which this sequence of events is achieved can be found, for example, in Shiokawa et al. (1998). As mentioned above, however, there is another train of thought which argues that substorm onset begins within the inner-tail current sheet, rather than at a near-Earth neutral line. In fact, the current disruption model (Chao et al., 1977; Lui, 1979) was developed primarily because of a lack of observational evidence for an X-type neutral line within about 20 \( R_E \) during substorm expansion. Disruption or diversion of the cross-tail current due to some current-driven instability can account quantitatively for the observed magnetic field reconfiguration in the near-Earth tail, as well as particle injections, and it was theorised that a tailward propagating rarefaction wave could then lead to plasma sheet thinning in the mid-tail region. Increasing evidence of near-Earth reconnection over the following years led to the further development of this model to bring it more in line with current observations. Lui (1991) developed a synthesis model which attempts to combine elements from a number of different substorm models to arrive at a coherent picture, providing a sequential evolution of the main observational substorm phenomena. A sketch of this synthesis substorm model is shown in Fig. 2.14, in which current disruption occurring inside ~20 \( R_E \) at substorm onset, launches a rarefaction wave down-tail which triggers reconnection at a distance of somewhere between 20 and 80 \( R_E \). However, the debate is still open as to whether it is the reconnection process which initiates current disruption or vice versa, or whether in fact there are additional factors which may influence the timing of phenomena occurring in this early stage.
Figure 2.14 Sketch of a synthesis substorm model with four stages of substorm development. The first, second and third columns illustrate substorm features in the ionosphere, noon-midnight meridian plane, and neutral sheet (equatorial projection) region of the magnetosphere, respectively (from Lui, 1991).
As mentioned above, other models have been suggested and developed over the years to account for a variety of phenomena which are observed to occur during substorms. The majority of these models emphasise the magnetospheric aspects of substorms, however, other models do exist which focus on the ionosphere and its coupling to the magnetosphere. The Kan (1990) model, for example, considers the consequences of instantaneously imposing an enhanced two cell convection pattern on the magnetosphere. This results in the reverberation of Alfvén waves between the ionosphere and the magnetotail, creating a distribution of field-aligned currents. The Rothwell et al. (1984, 1989) model considers the ionospheric consequences of an existing substorm current wedge. The finite delays imposed on the system by the inductance of field-aligned currents introduces a feedback instability. This mechanism allows the ionospheric and magnetospheric development of currents and fields to become uncoupled resulting in a poleward and westward expansion of the ionospheric portion of the substorm current wedge. A sheet of outward field-aligned current develops on the poleward edge of the auroral bulge, and goes unstable in the same way as the western edge of the current wedge. This potential drop becomes so strong that it alters the plasma flow in the plasma sheet.

2.3.3 Onset triggering mechanisms

The various models which exist for the onset of a substorm expansion deal with what, where, and in which order the various observed substorm phenomena occur. The question still remains, however, as to what actually triggers the initial instability which causes the onset to occur. There are essentially two trains of thought regarding this, firstly that it is an intrinsic magnetospheric parameter which goes critical at some predetermined level, and secondly that it is an external factor, such as something in the solar wind, which determines magnetospheric activity. One theory which supports the former argument is that of Self-Organised Criticality, or “SOC” (Bak et al., 1987). This concept was applied by Chang (1992, 1999) to the magnetosphere, suggesting that it can be naturally driven to a “scale-free” state in which energy release events (such as substorms) occur with no characteristic length or time scale. Examination of the statistics of, for example, AE shows that it obeys a
power law distribution. This might enable you to predict the size of a substorm, based on the frequency on which they were occurring, but does not let you predict what the critical point is. The idea that the triggering lies in the solar wind has also been explored. Recently, a comparison between the distributions of burst lifetimes of the solar wind driving functions \( v_B \) and \( \varepsilon \) and of the \( \text{AU} \) and \( |\text{AL}| \) indices (Freeman et al., 2000) showed that all distributions obey a similar power law. This suggests that the origin of the scale-free properties of the burst lifetime distributions of the AE indices (mentioned above) could lie in the solar wind. Lyons et al. (1997) also considers changes in the IMF to be the triggering events, including both northward turnings and reductions in \( |B_y| \). These changes in the IMF would be expected to lead to a reduction in the large scale electric field imparted to the magnetosphere from the solar wind. Lyons therefore suggests that it is this reduction which is related to the substorm onset, although he does not provide a physical explanation as to why this should be so.

2.3.4 Convection during substorms

All of these arguments aside, however, there is little debate that reconnection plays a role in the substorm unloading mechanism. It might therefore be expected on a simple basis that significant large-scale twin-vortex flows would be excited during substorms, corresponding in essence to those observed on the dayside cited above (Fig. 2.5b). Observational evidence for such flow excitation, however, has at best been ambiguous. In a recent study of Sondrestrom radar data, Blanchard et al. (1997) (following earlier work by de la Beaujardièe et al. (1991) and Blanchard et al. (1996)) measured the local reconnection rate by examining the ionospheric flow across the open-closed field line boundary, the position of the latter being estimated from ionospheric features observed by the radar and 630 nm auroral emission. They found that an increase in the reconnection rate occurs near midnight shortly after expansion phase onset, expanding to encompass a wider local time sector after ~20 min. However, the initial reconnection rate increase was mainly manifest in a poleward motion of the inferred open-closed field line boundary. Flows were found to become elevated only after an interval of ~30 min. Somewhat correspondingly, Weimer (1999) has
presented a statistical survey of low-altitude electric field data from the DE-2 spacecraft, separated according to the IMF direction and into substorm and non-substorm intervals (Fig. 2.15). The flow patterns for a given IMF orientation show a more pronounced 'Harang' asymmetry on the nightside during substorm intervals than during non-substorm intervals, but the total transpolar voltage values showed little overall difference.

On the other hand, Opgenoorth and Pellinen (1998), following earlier work by Grafe et al. (1987), have presented evidence for flow enhancements in the dusk auroral zone immediately following expansion phase onset in the midnight sector, leading to an immediate increase in the global 'directly driven' current system. They suggest, however, that diversion of the twin-vortex flow around the low-flow high-conductivity auroral bulge formed during the expansion phase (e.g. Kirkwood et al., 1988; Morelli et al., 1995; Yeoman et al., 2000; Khan et al., 2001), may play a role. Fox et al. (1999) have also reported observations of a surge of transpolar flow into the midnight sector associated with a substorm intensification, which they suggest was due to a burst of reconnection in the tail. Most recently, Grocott et al. (2000) have presented an analysis of SuperDARN radar flow data obtained during an isolated substorm, and have found evidence for the excitation of twin-vortex flow cells centred in the nightside ionosphere, which enhance the transpolar voltage by ~20 kV compared with pre-onset values (Fig. 2.16). Given these somewhat varied conclusions, taken together with rather clear theoretical expectations, further study of the important issue of large-scale ionospheric flow excitation during substorms is clearly warranted.

2.4 Other tail phenomena

Although substorms are generally considered to be the major magnetospheric response to dayside driving by the solar wind, they are by no means the only phenomenon which is observed in the geomagnetic tail. This is particularly evident during intervals of northward IMF when, as discussed above, the substorm cycle is believed to subside. However, whilst
Figure 2.15 Electric potentials derived at nine interplanetary magnetic field angles for (a) non-substorm and (b) substorm conditions. The angle is stepped from 90° (+Y) through 180° (-Z) to 270° (-Y) in 22.5° increments, as noted at the top left of each graph. The solid line contours show regions of positive potential, and the dashed line contours show regions of negative potential. The numbers at the bottom left and right show the minimum and maximum potentials respectively, in units of kV. The locations of the peak potentials are marked with plus symbols. An indication of whether the total trans-polar voltage for each IMF bin is greater (+) or less (-) for the substorm group is shown in the top right of each graph (adapted from Weimer, 1999).
Figure 2.16 Data from a pilot study of substorm associated convection showing (a) IMF $B_z$ from the WIND spacecraft, shifted by 27 mins to account for the spacecraft-ionosphere time lag, (b) maximum trans-polar voltage across the nightside ionosphere, with 5 point running mean, and (c) pseudo AE index, derived from 68 northern hemisphere magnetometers. The vertical dashed lines indicate enhancements in the trans-polar voltage which have associated intervals of southward IMF. The grey shaded area marks an interval of enhanced flow with no corresponding interval of southward IMF, but which does correspond to an enhancement in AE (from Grocott et al., 2000).
dayside flows during northward IMF are reasonably well delineated and understood within a simple conceptual framework (as shown in Fig. 2.1), the same cannot be said of nightside flows and their relationship to processes in the tail. Instead, a variety of phenomena have recently been reported, whose physical connections have yet to be fully established. Huang et al. (2001) have reported observations of quasi-sinusoidal nightside flow oscillations in SuperDARN radar data during an extended interval of modest northward IMF and small (typically <45°) clock angle. The flows had amplitudes ≈500 m s⁻¹ and a period of ≈1 h, and were associated with the formation of large-scale clockwise flow vortices in the post-midnight sector which subsequently propagated towards dawn. The authors associate these flows with global oscillations of an essentially closed tail. Walker et al. (1998, 2002), on the other hand, have reported the occurrence of latitudinally-restricted (~1° north-south) bursts of high-speed (~2 km s⁻¹) westward flow in the pre-midnight sector under rather similar interplanetary conditions (weak IMF with small-clock angle). These flow bursts had a ~12 min recurrence time (four main cycles were observed), and appear to have occurred at the equatorward edge of the dusk convection cell (Fig. 2.17). Walker et al. interpret the bursts as being due to sporadic energy release and field dipolarisation in the geomagnetic tail associated with a viscously-driven twin-vortex flow system, it being noted by Sutcliffe (1998) that Pi2 and weak (few tens of nT) midnight-sector bay activity occur during these events.

In yet another apparent class of nightside phenomena, bursty flow events having larger spatial scales and longer time scales have been reported. De la Beaujardière et al. (1994) report the occurrence of bursts of equatorward-directed flow in nightside Sondrestrom radar data, which take place during a 'quiet-time' interval in which the transverse components of the IMF were small and directed mainly northward. These bursts were initiated near the nightside open-closed field line boundary, had amplitudes up to several 100 m s⁻¹, and recur at ~1 h intervals, lasting on each occasion for a few tens of minutes (Fig. 2.18a). Simultaneous auroral data show that each flow pulse was preceded by an activation of the poleward-most arc system, in which a new east-west aligned arc formed poleward of the existing boundary, and subsequently moved equatorward, together with existing
Figure 2.17 Flow velocity observations during an interval of weak IMF with small clock angle. Successive panels show maps in geomagnetic coordinates of the vector velocity at two minute intervals during one evening sector flow burst. The dots represent grid positions and the line segments represent the magnitude and direction of the drift velocity vectors (from Walker et al., 2002).
Figure 2.18 (a) Propagation of an enhanced flow feature through the Goose Bay radar field of view. The colour scale indicates the gate by gate difference between the average and the measured line of sight velocity, as shown on the colour bar on the right. (b) Sondrestrom all-sky camera photographs of poleward boundary intensifications (PBIs) which preceded the flows in (a). North is at the top, east is to the right (from de la Beaujardiere, 1994).
precipitation structures (Fig. 2.18b). This behaviour strongly suggests an origin in bursts of reconnection in the ‘quiet-time’ tail. Poleward boundary auroral intensifications (PBIs) and arc ‘bifurcations’ have subsequently been shown to occur commonly under a wide variety of conditions, both during ‘quiet’ times, and in the growth, expansion and recovery phases of substorms (Lyons et al., 1999), often leading to the ejection of one or more north-south aligned auroral forms (called ‘auroral streamers’) towards lower latitudes (Henderson et al., 1998). These longitudinally-restricted ‘streamers’ have themselves been associated with the occurrence of narrow ‘bursty-bulk flow’ (BBF) channels of earthward-directed flow in the plasma sheet (Baumjohann et al., 1990; Angelopoulos et al., 1992), and the excitation of equatorward flow in the ionosphere (e.g. Yeoman and Lühr, 1997; Watanabe et al., 1998), Pi2 band activity, and longitudinally-localised injections of energetic particles at geostationary orbit (Sergeev et al., 1999). As discussed, for example, by Cowley (1998), and Cowley et al. (1998), these features are strongly suggestive of the occurrence of localised impulsive reconnection in the tail leading to plasma injection and flow excitation. During quiet times, at least, the reconnection site is presumed to be that lying in the more distant magnetotail beyond ~100 Re. The relationship between the ‘streamer’ structures and the large-scale ionospheric flow has yet to be investigated in detail. However, Senior et al. (2002) have recently reported the occurrence of large-scale bursty flows in the ‘quiet time’ nightside ionosphere during an interval of ‘intermediate’ clock angles >45°. These flows have a recurrence time of ~1 h, with substructure on tens of minutes time scales, similar to the bursts reported by de la Beaujardière et al. (1994), and take the form of surges of westward ‘return’ flow in the dusk convection cell, several degrees wide in latitude, and extending in local time from post-midnight towards dusk.

2.5 Summary

This chapter has given an overview of large-scale magnetospheric-ionspheric convection, and discussed the driving mechanisms both in the solar wind, and in the geomagnetic tail, which contribute to this phenomenon. From the point of view of this thesis, the most
important point to emphasise from this chapter is that these dayside and nightside processes, although related, are at a basic level decoupled and must therefore be considered independently if this large-scale convection is to be understood. The work discussed in Chapters 4 and 5 of this thesis investigates the tail-driven element of convection in two quite different scenarios. The first follows an interval of southward IMF, when substorm activity would be expected to control the tail's contribution to the convection pattern, and the second is under conditions of northward (but $B_z$-dominated) IMF, when magnetospheric activity is less well understood.
CHAPTER 3

Instrumentation and experimental techniques

The central focus of this thesis is the measurement of ionospheric convection velocities provided by the Super Dual Auroral Radar Network (SuperDARN). This chapter introduces SuperDARN, and the other instrumentation employed in the collection of data used here. It also briefly discusses the basic physical techniques upon which these instruments are based, and some of the analysis techniques used to exploit the data.

3.1 The Super Dual Auroral Radar Network

SuperDARN is an international array of HF coherent radars spanning the auroral regions of both the northern and southern hemispheres (Greenwald et al., 1995). Its primary use is the measurement of ionospheric plasma Doppler velocities and, owing to its high spatial coverage, it is ideally suited for use in the derivation of large-scale convection patterns. SuperDARN was born in 1983 with the deployment of the Goose Bay radar in Canada. It followed the related development of several paired VHF radar systems including the Scandinavian Twin Auroral Radar Experiment (STARE) (Greenwald et al., 1978), the Sweden And Britain Radar Experiment (SABRE) (Nielsen et al., 1983), and the Bistatic Auroral Radar System (BARS) (McNamara et al., 1983). These VHF radars were designed to measure the Doppler velocity of E-region irregularities over a $1.6\times10^5 \text{ km}^2$ area. During the early 1980s however, some of the shortcomings of the E-region coherent scatter technique for convection studies were becoming apparent, and experiments involving F-region scatter led to the development of an HF system which made observations of F-region irregularities over a significantly larger field-of-view (covering approximately $4\times10^6 \text{ km}^2$). This system then formed the basis of a number of radars which were developed
Chapter 3 Instrumentation and experimental techniques

and deployed in both northern and southern hemispheres over the following ~20 years to form what has become known as SuperDARN. A description of the SuperDARN radars is given below. First, however, some of the fundamental ideas regarding the use of coherent backscatter radars in observing the ionosphere are discussed.

3.1.1 Nature of coherent backscatter

Coherent-scatter radars are sensitive to Bragg scattering from plasma waves produced by small-scale electron density irregularities in the ionosphere. The most common mechanism for generating F-region irregularities is the gradient drift mechanism (Simon, 1963; Fejer and Kelly, 1980). This is illustrated schematically in Fig. 3.1 which shows a portion of the perturbed boundary between two regions of different density. In the F-region ion mobility can still involve a small Pedersen drift whereas electrons drift purely in the Hall direction. This can introduce a charge separation and, consequently, a polarisation electric field, \( \delta E \), resulting in a net plasma drift in the direction \( \delta E \times B_0 \) (where \( B_0 \) is the ionospheric magnetic field). If the density gradient is perpendicular to the ambient electric field, \( E_0 \), this additional drift will cause the low density plasma to be forced into the high density region and vice versa, leading to the growth of plasma waves on the surface of the density gradient boundary. Unlike in E-region scatter, the phase speed of these waves is effectively zero such that by measuring their speed, HF radars are measuring a proxy for the plasma convection velocity. This has been shown quantitatively by recent comparisons of F-region irregularity drift velocities measured by HF radars and ion drift velocities measured by incoherent scatter radars (Davies et al., 1999, 2000).

Ionospheric irregularities are magnetic field-aligned, i.e. their wave vector is directed closely orthogonal to the magnetic field. As a consequence of this, the incident radar signal must also be orthogonal to the magnetic field in order for the scattered signal to return to the radar. The altitude at which orthogonality can be achieved depends largely on the latitude of the radar. At high latitudes where the magnetic field has a large vertical component, orthogonality is likely to occur at lower altitudes, i.e. at E-region heights. Studies of
Figure 3.1 The gradient drift instability in the F region can occur when the ambient electric field is perpendicular to the plasma density gradient, for example, near the edge of auroral forms. The principal charge separation mechanism at F-region altitudes is the ion Pedersen drift (from McWilliams, 2001).
F-region irregularities have often therefore been confined to mid or low-latitudes, where orthogonality is reached at higher altitudes. This, of course, assumes straight line radio wave propagation, which is true of VHF (and UHF) radars. For HF radars however, orthogonality can be achieved at high-latitudes since the F-region electron density is sufficiently high that the waves are refracted. An illustration of how orthogonality can be achieved for different radio frequencies at different altitude and latitudes is shown in Fig. 3.2.

Although it is therefore possible to obtain backscatter from high-latitude F-region irregularities using HF radars, it is still by no means straightforward. The refractive index of the F-region plasma, for example, is not constant meaning that backscatter will originate at many different ranges and altitudes. Indeed, in some cases a signal can be refracted to such an extent that it hits the ground in front of the radar and 'hops' forward to produce multi-hop waves. Any ground backscatter, or 'ground-scatter', can be identified at the receiver by its spectral characteristics. A number of these possible ray paths are illustrated in Fig. 3.3. Ray \( A \) has a low elevation angle and backscatters in the E-region with the possibility of multiple hops occurring. Ray \( B \) has a higher elevation angle and backscatters in both the E and F-regions. In this case the second 'hop' is also shown illustrating how, for example, F-region scatter can be observed at multiple ranges. Ray \( C \) has the highest elevation angle and ionospheric refraction is insufficient to produce reflection, so the ray penetrates the ionosphere. In this case, although ionospheric backscatter can be observed in the E and F-regions, no ground backscatter or far range ionospheric backscatter is produced.

### 3.1.2 The SuperDARN radars

The HF radars which comprise SuperDARN utilise ionospheric refraction to achieve orthogonality with the magnetic field as described above. Since the amount of refraction is dependent on the ionospheric electron density which varies diurnally, annually, and with geomagnetic activity, the radars are designed to operate over an extended frequency range. SuperDARN radars cover the range 8 to 20 MHz, which enables them to achieve similar
Figure 3.2 A schematic of possible ray paths from VHF and HF radars ($k_i$ being the incident wavevector and $k_s$ being the scattered wavevector). Paths 1 and 2 show backscatter being obtained from magnetic field-orthogonal VHF rays in the F-region at mid-latitudes and in the E-region at high latitudes, respectively. Path 3 shows how VHF rays at high latitudes either penetrate the ionosphere or are scattered into space owing to an inability to reach orthogonality. Path 4 shows how high-latitude HF rays can achieve orthogonality via ionospheric refraction (adapted from Greenwald et al., 1995).
Figure 3.3 A schematic of possible propagation modes and regions from which backscatter can occur. Ranges and altitudes are approximate and depend on ionospheric conditions. Three rays are illustrated: A E-region mode; B F-region mode (producing both near and far range backscatter); C a ray that penetrates the ionosphere (from Milan et al., 1997).
operational conditions over a factor of more than six in peak electron density. They are also frequency agile, allowing observations at two or more frequencies to be interwoven. The antenna array consists of 16 log-periodic antennas (illustrated in Fig. 3.4 which shows a photograph of the Hankasalmi radar in Finland), signals from which are phased electronically allowing the beam to be steered in 16 directions. Measurements are made along the direction of the beam and velocity information therefore only contains the line-of-sight component of the full vector velocity. The beamwidth is dependent on the radar operating frequency and ranges from 2.5° at 20 MHz to 6° at 8 MHz. The azimuthal separation of the beams, however, is fixed at 3.24°, giving a total field-of-view which covers a 52° azimuthal sector. This is illustrated in Fig. 3.5 which shows the fields-of-view of all 15 radars in both the northern and southern hemispheres, clearly demonstrating the ability of SuperDARN to image large portions of the high-latitude convection pattern. Details of each radar (identified by the ‘letters’ in Fig. 3.5) are given in Table 3.1.

The range resolution of the measurements is determined by the transmitted pulse length, which is 300μs for ‘common mode’ operations. This equates to a resolution of 45 km, although shorter pulse lengths are sometimes used to increase the resolution of the radars over a smaller field-of-view (one example of a ‘special’ mode). Each beam is divided into 75 range gates such that in the common operating mode the radar covers over 3000 km in range. The total time taken for one complete radar ‘scan’ is two minutes for the common mode, with a dwell time of 7 s per beam. In fast-common mode, the radars make a complete scan every minute, with a dwell time of 3 s per beam. Common and fast-common mode operations make up at least 50% of the total operating schedule. The remainder of the schedule is used for special, or ‘discretionary’ modes, which consist of numerous variations of the standard scan such as the high spatial resolution mode mentioned above. Other discretionary modes include, for example, limiting a scan to a subset of the 16 beams, to improve the temporal resolution of measurements.
Figure 3.4 A photograph of the Hankasalmi SuperDARN radar in Finland.
Figure 3.5 The locations and fields-of-view of the (a) northern and (b) southern hemisphere SuperDARN radars.
<table>
<thead>
<tr>
<th>Radar name</th>
<th>Radar code</th>
<th>Geographic latitude</th>
<th>Geographic longitude</th>
<th>Year of initial operation</th>
</tr>
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<tr>
<td>Hankasalmi</td>
<td>F</td>
<td>62.32°N</td>
<td>26.61°E</td>
<td>1995</td>
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<tr>
<td>Pthykkvibaer</td>
<td>E</td>
<td>63.77°N</td>
<td>20.54°W</td>
<td>1995</td>
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<td>W</td>
<td>63.86°N</td>
<td>22.02°W</td>
<td>1994</td>
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<td>G</td>
<td>53.32°N</td>
<td>60.46°W</td>
<td>1983</td>
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<tr>
<td>Kapuskasing</td>
<td>K</td>
<td>49.39°N</td>
<td>82.32°W</td>
<td>1994</td>
</tr>
<tr>
<td>Saskatoon</td>
<td>T</td>
<td>52.16°N</td>
<td>106.53°W</td>
<td>1994</td>
</tr>
<tr>
<td>Prince George</td>
<td>B</td>
<td>53.98°N</td>
<td>122.59°W</td>
<td>2000</td>
</tr>
<tr>
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<td>A</td>
<td>57.6°N</td>
<td>152.2°W</td>
<td>2000</td>
</tr>
<tr>
<td>King Salmon</td>
<td>C</td>
<td>57.0°N</td>
<td>157.0°W</td>
<td>2001</td>
</tr>
<tr>
<td>Halley</td>
<td>H</td>
<td>75.52°S</td>
<td>26.63°W</td>
<td>1989</td>
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<tr>
<td>SANAE</td>
<td>D</td>
<td>71.68°S</td>
<td>2.85°W</td>
<td>1996</td>
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<td>Syowa South</td>
<td>J</td>
<td>69.0°S</td>
<td>39.58°E</td>
<td>1995</td>
</tr>
<tr>
<td>Syowa East</td>
<td>N</td>
<td>69.0°S</td>
<td>39.61°E</td>
<td>1997</td>
</tr>
<tr>
<td>Kerguelen</td>
<td>P</td>
<td>49.35°S</td>
<td>70.26°E</td>
<td>2001</td>
</tr>
<tr>
<td>TIGER</td>
<td>R</td>
<td>43.38°S</td>
<td>147.23°E</td>
<td>2000</td>
</tr>
</tbody>
</table>

Table 3.1 The geographical coordinates and year of initial operation for the northern and southern hemisphere SuperDARN radars.
3.1.3 The map potential model

As mentioned above, velocity measurements by the SuperDARN radars are only line-of-sight velocities. Whilst these do still provide valuable information of the motion of the plasma, it is obviously more useful to know the full vector velocity if a true picture of the convection pattern is to be derived. A number of methods have been developed in an attempt to achieve this, the most obvious being to combine two co-located line-of-sight velocity measurements from the overlapping fields-of-view of a radar pair. The main drawback of this 'merging' method, is that many of the line-of-sight velocities will not overlap, severely reducing the area over which the convection pattern can be imaged (see, for example, Fig. 3.6 (c) compared with Fig. 3.6 (b)). One technique which has been developed in an attempt to overcome this problem is employed by the 'Map Potential' model, developed by Ruohoniemi and Baker (1998). This is based on the idea that multiple line-of-sight velocities serve to constrain the possibilities for the large-scale convection pattern, which can be determined by mathematical fitting procedures, as will be discussed below.

In the Map Potential model, the line-of-sight velocities are first filtered to remove data with error estimates greater than 200 m s\(^{-1}\), and to remove ground-scatter. The remaining velocities are then temporally and spatially averaged on to a polar grid (an example of which is shown in Fig. 3.6 (a)). This results in a marked improvement in the smoothness of the velocity maps. These preprocessed velocities are then used to determine a best-fit solution for the electrostatic potential, which is expressed in spherical harmonics. The electrostatic potential at every point on the grid is related to the convection electric field by \(\mathbf{E} = -\nabla \varphi\), which is simply related to the velocity via Eq. 1.1 (\(\mathbf{E} \times \mathbf{B}\) drift). The fitted velocity is then obtained by effectively minimising the residual between the line-of-sight velocity and the projection of the fitted velocity onto the line-of-sight direction. The equipotentials of the best-fit solution then represent the plasma streamlines of the modelled convection pattern (see, for example, Fig. 3.6 (d)).
Figure 3.6 Exemplar SuperDARN data after various levels of analysis. (a) Filtered, averaged, line-of-sight velocity data from the Goose Bay radar, shown on the global grid used for spatially averaging the data. (b) The averaged line-of-sight velocity data from four of the northern hemisphere Super DARN radars (indicated by their letter codes, listed in Table 3.1). (c) Convection velocity vectors obtained by merging the overlapping line-of-sight velocity values in (b). (d) Solution for the global convection pattern obtained by fitting the line-of-sight velocity data in (b) and data from a statistical convection model to a 4th order expansion of the electrostatic potential in spherical harmonics (adapted from Ruohoniemi and Baker, 1998).
Chapter 3 Instrumentation and experimental techniques

If measurements were available over the entire polar cap, then this method alone would provide an accurate image of the global convection pattern. However, this is not the case and so additional constraints must be imposed on the solution for it to stabilise. Information from the statistical model of Ruohoniemi and Greenwald (1996), parameterised by concurrent IMF conditions, is therefore used to provide additional velocity measurements in order to bound each term in the spherical harmonic expansion. A higher order expansion will therefore involve a larger number of statistical data points being used, however, the weighting of these points can be modified such the net model input to the fit remains constant. A number of additional constraints are also imposed to further improve the pattern that is derived in regions of poor data coverage. Firstly, the centre of the spherical harmonic expansion can be shifted from the magnetic pole along the noon-midnight meridian if it seems apparent from the data that there is a day-night asymmetry in the location of the polar cap. It is also necessary to define a lower-latitude convection limit relative to the centre of the convection pattern such that the electric potential is forced to zero where the data implies it does.

One final choice available to the user is what type of velocity vectors to plot. The fitted velocities (described above) will obviously just follow the equipotentials contours and provide little extra information on the convection pattern. However, the best-fit velocity will not always be a good fit to the line-of-sight velocity, and the residual between it and the line-of-sight velocity may well be high, particularly in regions where small-scale spatial structures have not been defined by the fit. It is therefore often useful to plot what are called 'true' vectors. These vectors are resolved using the line-of-sight velocity and the tangential component of the fitted velocity. This ensures that nothing of the original data is lost, in contrast to relying purely on the best-fit result.
3.2 Ground magnetometer networks

The second main piece of instrumentation employed in the collection of data for this thesis is the magnetometer. Six northern hemisphere arrays of magnetometers have been used, which span approximately the same range of local time as the SuperDARN radars above. The locations of specific magnetometers which have been used in Chapters 4 and 5 are shown in Figs. 4.1 (b) and 5.6, respectively. Two that are located in the Scandinavian sector are the International Monitor for Auroral Geomagnetic Effects (IMAGE) (Lühr et al., 1998) and the Sub-Auroral Magnetometer Network (SAMNET) (Yeoman et al., 1990). Data from the Greenland Magnetometer Chain (Friis-Christensen et al., 1985), which is operated by the Danish Meteorological Institute (DMI), have also been used, in particular data from its west coast chain. Finally, three arrays in the USA and Canada have also been used. They are the Canadian Auroral Network for the Open Program Unified Study (CANOPUS) (Grant et al., 1992), the Magnetometer Array for Cusp and Cleft Studies (MACCS) (Hughes and Engebretson, 1997), and an array operated by the Geological Survey of Canada (GSC).

Perturbation magnetic field measurements from all six arrays are presented in this thesis in $H$, $D$, and $Z$, coordinates (where $H$ is local magnetic north, $D$ is local magnetic east, and $Z$ is vertically down), at varying resolutions from 1-20 s (unless otherwise stated). The coordinate system upon which these directions are based is the Altitude Adjusted Corrected Geomagnetic (AACGM) system, a development of the PACE system discussed by Baker and Wing (1989).

3.2.1 The fluxgate magnetometer

This is the most common instrument employed in the measurement of magnetic fields. A schematic illustration showing the basic components of a fluxgate magnetometer is presented in Fig. 3.7. The magnetic field sensor is essentially just a transformer wound around a high-permeability core. The primary winding of the transformer is excited by a high-frequency current, and the core is driven into saturation on each half-cycle of excitation. The secondary winding detects a time-varying voltage which is dependant on
**Figure 3.7** Schematic illustration of the basic components of a fluxgate magnetometer (from Kivelson and Russell, 1995).
any external magnetic field. For the case where this external field is zero, only odd harmonics of the drive frequency are present in the output. Otherwise, the output reaches saturation in one half-cycle sooner than it does in the other half. This lack of symmetry introduces even harmonics into the output signal. The amplitude and phase of all the even harmonics are proportional to the magnitude and direction of the field along the transformer axis. For geophysical observatories, three orthogonal magnetometers are used to determine the ambient 3-D magnetic field. Fluxgate magnetometers are not absolute instruments, but can be accurately calibrated to give the absolute field. This can be achieved using other types of magnetometer which directly measure the absolute field (such as the proton-precession magnetometer). However, their workings are not pertinent to the current discussion.

3.3 Geostationary spacecraft

A number of geostationary spacecraft have been employed to provide additional magnetic field and particle measurements of geospace for use in this thesis. These are briefly described below.

3.3.1 The Geostationary Operational Environmental Satellites

Magnetometer data have been obtained by the Space Environment Monitor (SEM) on-board the Geostationary Operational Environmental Satellite, GOES-8 (Singer et al., 1996). The SEM instrument consists of an X-ray sensor, a particle detector and a magnetometer. The magnetometer consists of a twin-fluxgate spinning sensor allowing Earth’s magnetic field to be described in 3-D. Field strength changes as small as 0.2 nT can be measured and the magnetometer samples the field every 0.75 s. Four of these values constitute a frame and are sent to the ground station together. The high and low values in the frame are discarded and the average of the two remaining values is recorded.
3.3.2 Los Alamos National Laboratory spacecraft

Geosynchronous particle injections have been monitored using the Synchronous Orbit Particle Analyser (SOPA) instrument on-board the Los Alamos National Laboratory (LANL) spacecraft LANL-97A and 1994-084 (Belian et al., 1992). The SOPA instrument is designed to provide high-spatial and high-temporal resolution energetic particle measurements at geosynchronous orbit on spinning satellites. As such it monitors electrons (50 keV to 2 MeV), protons (50 keV to 50 MeV), as well as helium, carbon, nitrogen, and oxygen ions individually. The instrument consists of three solid state detector telescopes (T1, T2 and T3) that accept particles from three different directions relative to the spacecraft spin axis. Each telescope consists of a thin, 4 \( \mu \)m, 10 mm\(^2\) front detector followed by a thick, 3000 \( \mu \)m, 25 mm\(^2\) back detector. A collimator, with 11° (full width) field of view fronts the detector stack.

3.4 Polar auroral images

Images of the aurora are provided by the Visible Imaging System (VIS) on the Polar spacecraft (Frank et al., 1995). Polar orbits the Earth in an elliptical orbit of \( \sim 1.8-9 \) \( R_E \), with an apogee which was originally over the north pole but has been advancing equatorward at \( \sim 15° \) per year. VIS is a set of three low-light-level cameras, two of which share primary and some secondary optics and are designed to provide images of the night-time auroral oval at visible wavelengths. A third camera (the VIS Earth Camera) is used to monitor the directions of the fields-of-view of these sensitive auroral cameras with respect to sunlit Earth. It monitors the aurora at far-ultraviolet wavelengths within a broad passband of 124-149 nm. This camera can provide full images of Earth from radial distances of 5.8 \( R_E \) giving a spatial resolution in the ionosphere of \( \sim 50 \) km. Images are provided approximately every 5 min and consist of 32.5 s integrations of UV photons primarily from atomic oxygen emission at a wavelength of 130.4 nm.
3.5 DMSP auroral particle instruments

Measurements of ion and electron fluxes by the SSJ/4 instrument on board the Defense Meteorological Satellite Program (DMSP) F12, F13, and F14 spacecraft (Hardy et al., 1984) have been employed to examine the patterns of polar particle precipitation and their relationship to the plasma flow. From the measured field-aligned plasma populations the location of high-latitude magnetospheric plasma regions near 830 km altitude are inferred (e.g. Newell and Meng, 1992). The spacecraft is three-axis stabilised, with the instruments pointing toward zenith at all times. The particle detectors provide 1 s resolution spectra of ion and electron fluxes between 30 eV and 30 keV.

3.6 Upstream interplanetary parameters

Measurements of interplanetary parameters such as the proton number density \( n_p \), the plasma speed \( v_p \), and the three GSM components of the IMF \( B_x, B_y, B_z \) are made upstream of the Earth by instruments on-board the Advanced Composition Explorer (ACE) (Stone et al., 1998) (see Fig. 3.8 for a definition of the GSM coordinate system). The ACE spacecraft orbits the Sun at the Earth-Sun Lagrangian point (L1), which is located upstream of the Earth at a distance of 1.5 million km (~220 R_E). By orbiting at the L1 point, ACE remains in a relatively constant position with respect to the Earth as the Earth orbits the Sun.

3.6.1 The Solar Wind, Electron, Proton and Alpha Monitor

The purpose of the Solar Wind Electron, Proton, and Alpha Monitor (SWEPAM) (McComas et al., 1998) is to provide detailed knowledge of solar wind conditions. The instrument provides high quality measurements of electron and ion fluxes in the low-energy solar wind range (1 eV to 1.24 keV electrons and 260 eV to 35 keV ions). Simultaneous electron and ion measurements are made using two separate instruments. Each instrument consists of a curved plate, >90° bending angle electrostatic analyzer (ESA) followed by
Figure 3.8 The GSM coordinate system. The x-axis is defined along the line connecting the center of the Sun to the center of the Earth. The origin is defined at the center of the Earth, and is positive towards the Sun. The y-axis is defined as the cross product of the GSM x-axis and the magnetic dipole axis, directed positive towards dusk. The z-axis is defined as the cross product of the x- and y-axes. The magnetic dipole axis lies within the x-z plane.
biased channel electron multipliers (CEMs) spaced along the exit apertures of the ESAs. Different CEMs sample different portions of the fan shaped fields-of-view allowing measurement of particle arrival directions relative to a spacecraft coordinate system of azimuthal and polar angle. This local coordinate system is then converted into GSM coordinates for data analysis.

3.6.2 The Magnetometer Instrument

The magnetometer instrument (MAG) (Smith et al., 1999) measures the direction and strength of the magnetic field to establish large scale structure and fluctuation characteristics of the IMF upstream of Earth. The two magnetometers on ACE are wide-range (±0.004 nT to 65536 nT) triaxial fluxgate magnetometers. They are mounted remotely from the spacecraft on separate booms in order to reduce any effect of magnetics from the spacecraft and other instruments. They measure the amplitude and direction of the IMF thirty times per second and can do Fast Fourier Analysis on these measurements to get the frequency spectrum of fluctuations in the magnetic field.

3.7 Summary

In this chapter the diverse range of instruments employed in the collection of data used in this thesis have been described. The primary focus of study in the following chapters are measurements of ionospheric convection velocities by the SuperDARN HF coherent radars. This facility is unique in that it can provide information on the large-scale convection pattern over most of the northern (and some of the southern) hemisphere polar ionosphere. When combined with measurements of the magnetic field on the ground, in the magnetosphere, and in upstream interplanetary space, SuperDARN becomes an invaluable tool in the investigation of solar wind-magnetosphere-ionosphere interactions. Coincident observations of the aurora, along with energetic particle measurements in the ionosphere and in the geostationary environment also extend the capability of diagnosing intrinsic
magnetospheric processes. The work discussed in the following two chapters fully exploits these available data resources in studying the ionospheric convective response to different magnetospheric and interplanetary conditions.
This chapter describes a study of the flows which occurred during an isolated substorm on 2 December 1999. As discussed in Chapter 2, it is expected that large-scale twin-vortex flows should be excited during substorms, however, this is not a phenomenon which has been widely reported. Although the study of flows during substorms seems in principle simple, the intervention of several factors introduces significant difficulties into this undertaking. The first is that substorm intervals are usually associated with periods of large and variable negative IMF $B_z$, which will result in large variations of the ionospheric flow through modulated magnetopause reconnection. These variations may be expected to be at least as large as those associated with nightside reconnection and substorms, such that the flow variations associated with the substorms may be obscured. Second, substorms are generally initiated in the ionosphere on field lines mapping to $\sim 65^\circ$. This latitude is close to the equatorward edge of the SuperDARN field of view (in normal scan mode), so that the substorm-effected region may only be partially imaged. Third, it is very often the case that SuperDARN radar backscatter drops out during intervals of magnetic disturbance due to precipitation-induced D–region radio absorption (Milan et al., 1996; Yeoman and Lühr, 1997). In this case the evolution of the flow during the substorm cannot be properly followed after the onset of the expansion phase.

The substorm studied here occurred under somewhat fortuitous circumstances, such that the above difficulties were largely circumvented, making it ideally suited for an investigation of such flows. First, the substorm occurred during an interval of very steady northward IMF (and large negative $B_y$), such that the flows driven from the dayside may be expected to have been steady in character and modest in magnitude. Second, because of these overall
relatively quiet conditions, the substorm occurred at higher latitudes than usual, with the electrojet centred near \( \sim 70^\circ \), and was thus located well within the region of usual SuperDARN coverage. Furthermore, the substorm occurred in the pre-midnight sector centrally within the region viewed by the six northern hemisphere radars then operating, so that the flows both within the substorm-disturbed region, and in the regions both to its east and west, were well monitored during the disturbance. Third, backscatter was observed throughout the interval essentially across the full range of local times covered by the radars (though still dropping out within part of the substorm bulge region itself), so that good estimates can be made of the overall voltage associated with the flow. This was probably due to the high-latitude nature of the substorm, such that the enhanced D region lay poleward of where the HF radar beams traversed that layer of the ionosphere.

4.1 Observations overview

The ground and space observations made during the substorm are discussed below. An overview of the interplanetary and geomagnetic conditions during an expanded interval surrounding the substorm is presented initially, followed by a more detailed discussion of the magnetic, flow, and auroral data during the substorm itself. The locations of the main instrumentation employed in obtaining these data (discussed in detail in Chapter 3) are shown in Fig. 4.1. At the time of the interval described here, the northern hemisphere SuperDARN network consisted of six radars, whose fields of view covered approximately 12 h of magnetic local time (MLT). This is illustrated in Fig. 4.1a, which shows a view looking onto the northern magnetic pole. With increasing MLT, the fields of view of the Saskatoon (T), Kapuskasing (K), Goose Bay (G), Iceland West (W), Iceland East (E), and Finland (F) radars are shown on a geomagnetic grid at 0100 UT (a central time during the study, corresponding to maximum magnetic/flow disturbance during the substorm), extending from the pole to 60° latitude, with noon at the top and dusk to the left. The fields-of-view of the three radars whose data will be displayed in detail are shaded blue, with data being displayed from the beam directions marked by the red lines. All six radars were
Figure 4.1  (a) Fields-of-view of the six northern hemisphere SuperDARN radars at 0100 UT, plotted on a geomagnetic grid from the pole to 60°, with 12 MLT at the top and dusk to the left. Fields-of-view coloured blue are those of the three radars for which detailed line-of-sight measurements will be discussed, using the beams indicated in red. (b) Shows ground-based magnetometer locations and geostationary spacecraft footprints at 0100 UT on the same grid. Coloured magnetometer locations are those for which time-series plots will be shown. The black oval represents the ionospheric footprint of geostationary orbit (specifically that of the GOES-8 spacecraft). On it are plotted the locations of the GOES-8, LANL-97A, and 1994-084 spacecraft.
operating in the ‘standard’ mode discussed in Chapter 3, and large-scale maps of the high-
latitude convection have been derived from these data using the ‘Map Potential’ model also
discussed in Chapter 3. In this study, spherical harmonic fits using terms up to sixth order
are employed to fit the radar data, as deemed appropriate from the good overall coverage of
the data.

Fig. 4.1b shows the locations of the ground magnetic stations employed, on the same
magnetic grid at 0100 UT as in Fig. 4.1a. Measurements are provided by magnetometers
from the six northern hemisphere arrays detailed in Chapter 3. The identifier codes of
specific magnetometer stations which are of particular interest are also indicated in the
figure. Data from those at lower latitudes and colour-coded green (i.e. PBQ, NAQ, and
FAR) have been band-pass filtered (20-200 seconds) to provide information on Pi 2 signals.
Those at latitudes ~70°-75° and colour coded red (i.e. CHX, IQA, GHB, AMK, SCO, and
BJN) define the local time extent of the principal magnetic disturbances during the
substorm, spanning ~8 h of MLT from post-dusk, through midnight, to pre-dawn. In
addition, data are shown from the Greenland west coast latitudinal chain STF, SKT, GHB,
FHB, and NAQ, of which GHB and NAQ are colour-coded red and green as just indicated,
while the remainder are colour-coded blue. This chain spans the substorm electrojet
between ~66° and ~74° magnetic latitude. Also indicated on the figure by the coloured
triangles are the footprints of three geostationary spacecraft, which will be discussed below.

4.1.1 Upstream interplanetary conditions

Interplanetary conditions were monitored by the ACE spacecraft (see Chapter 3), located
upstream of the Earth at GSM coordinates \((X,Y,Z) = (+221,+21,-25) \, R_E\) (the variation of the
spacecraft position over the interval was not significant). Fig. 4.2a presents data from the
ACE spacecraft during the 10 h interval from 1900 UT on 1 December to 0500 UT on
2 December 1999, lagged by 74 min to account for the propagation delay of field changes
from ACE to the dayside ionosphere. This delay has been estimated using the method of
Khan and Cowley (1999), and includes the propagation time in the solar wind upstream of
Figure 4.2  (a) Upstream interplanetary observations from the ACE spacecraft, lagged by 74 min to account for the propagation delay to the ionosphere. The top two panels show solar wind density and velocity data, while the bottom three panels show IMF data in GSM co-ordinates, for 1900 UT on 1 December to 0500 UT on 2 December 1999. The times of substorm expansion phase onset and recovery onset are marked with vertical dashed lines. (b) Shows H-component magnetic field measurements from the azimuthal magnetometer array shown by the red dots in Fig. 4.1b. The separation between magnetometer baselines (horizontal dotted lines) is 300 nT. These baselines have been taken as the field measured at each station at 0400 UT, as discussed in the text. Vertical arrows indicate the time of magnetic local midnight. Magnetic midnight for station CHX occurs at ~0526 UT, just beyond the interval displayed.
the bow shock, the frozen-in transit time across the subsolar magnetosheath, and the Alfvénic propagation time along open field lines from the subsolar magnetopause to the ionosphere. The vertical dashed lines on this and subsequent figures indicate the onset time of the substorm expansion at 0044 UT, and the beginning of the recovery phase at 0106 UT. Details of the determination of these times will be discussed below. The top two panels show the solar wind proton number density \(n_p\) and speed \(v_p\) from ACE/SW EPAM (for which data were available only up to 0330 UT lagged time). During this interval the density varied between 5 and 20 cm\(^{-3}\), and the velocity between 330 and 380 km s\(^{-1}\). However, it is apparent that during the substorm interval both the density and velocity were relatively steady at \(
approx 12\) cm\(^{-3}\) and \(
approx 350\) km s\(^{-1}\), respectively. The bottom three panels illustrate the three components of the IMF in GSM coordinates from ACE/MAG. Throughout most of the interval \(B_x\) remained small and negative, typically 0 to \(-5\) nT, while \(B_y\) was large and negative, around \(-10\) nT. \(B_z\) was also negative until \(
approx 2050\) UT (lagged time), thereafter remaining close to zero until \(
approx 0010\) UT. Between \(\approx 0010\) UT and \(\approx 0215\) UT \(B_z\) was consistently northward, and remained at a constant \(+5\) nT during the substorm expansion phase. At \(\approx 0215\) UT it underwent a brief southward excursion, before returning northward for the remainder of the interval.

4.1.2 Ground magnetic data overview

Fig. 4.2b presents \(H\) component measurements from the six ground magnetometers which comprise the \(\sim 120^\circ\) longitudinal array coloured red in Fig. 4.1b. The vertical arrows indicate magnetic local midnight for each of the stations (midnight for CHX occurs at \(\approx 0526\) UT, just beyond the interval displayed). The horizontal dotted lines are baselines for the magnetic disturbance observed at each station, the choice of which is discussed below. An initial magnetic disturbance starts just after 1900 UT, coinciding with the interval of negative IMF \(B_z\) mentioned above. However, these perturbations start to decay simultaneously with the northward turning of the IMF at \(\approx 2050\) UT, with all traces returning to near baseline by \(\approx 0000\) UT. Then, at \(\approx 0044\) UT (first dashed line) a sharp negative bay onset begins in the midnight sector, with small negative precursory activity starting at
Chapter 4  Excitation of twin vortex flow during an isolated substorm

A peak disturbance of ~275 nT was observed at AMK at 0055 UT. UV imagery to be shown below demonstrate that the main auroral disturbance spanned the interval from ~2000 to ~0100 MLT, thus encompassing stations IQA, GHB, and AMK (located at 2116, 2250, and 2355 MLT at 0100 UT). Fig. 4.2b demonstrates that magnetic perturbations were also observed outside this region, with weak negative disturbances peaking at ~50 nT being observed at CHX at ~1930 MLT, variable fields of ~75 nT amplitude at SCO at ~0110 MLT, and positive perturbations peaking at 125 nT at BJN at ~0330 MLT. Thus, as previously emphasised by Opgenoorth and Pellinen (1998), magnetic disturbances occur during the expansion phase over a broad range of MLT (greater than 8 h in this case), and are not confined to the range of local times occupied by the auroral bulge. These disturbances will be related below to changes in the flow pattern that occur during the substorm. An equally rapid bay recovery began at ~0106 UT (second vertical dashed line). The main interval of disturbance was concluded by ~0120 UT, with more gradual variations towards baseline values occurring after that.

4.1.3 Greenland west magnetic data

The location of the meridional array of west coast Greenland magnetometers makes it ideally suited to provide data from the substorm-disturbed region itself. Fig. 4.3 shows magnetic measurements from this array (the 'blue' array in Fig. 4.1b), which were located near 2300 MLT, and thus centrally within the substorm-disturbed region at the time of substorm onset. Data are shown for an 80 min interval spanning the substorm, from 0020 to 0140 UT on 2 December. The vertical dashed lines show the times of onset of the expansion and recovery phases as in Fig. 4.2. Panel (i) shows the H component at stations NAQ to STF, spanning magnetic latitudes from ~66° to ~73°. The largest negative disturbance occurred at GHB at ~71°, reaching ~225 nT at 0055 UT. Consistently smaller values were observed both poleward and equatorward, while only positive perturbations were observed at NAQ at ~66°. These data thus suggest that the centre of the westward electrojet was located near GHB at ~71°. The onset times of the expansion and recovery phases, 0044 UT and 0106 UT respectively, have thus been based on the onset and decay of
Figure 4.3  H, D, and Z-component magnetic field measurements from the meridional Greenland west coast magnetometer array (see Fig. 4.1b), for 0020-0140 UT on 2 December 1999. The separation between magnetometer baselines (horizontal dotted lines as in Fig. 2b) is 250 nT. Vertical dashed lines are as in Fig. 4.2.
the negative bay at GHB. Although the expansion onset time is similar at all stations within the electrojet region, GHB is the last station to observe the start of the recovery phase. The location of the centre of the disturbance is confirmed by the Z component data displayed in panel (iii), which show near-zero perturbations throughout the interval at station GHB, with negative perturbations at FHB and NAQ in the equatorward region, and positive perturbations at SKT and STF in the poleward region. The negative Z perturbations peak at station FHB, while the positive perturbations peak at STF (and fall to smaller values at GDH at ~76° and UMQ at ~77°, data not shown). These data thus suggest a westward electrojet spanning ~68°-73°, centred near ~71°. The D component data are shown in panel (ii). Relatively strong negative perturbations observed at STF in the poleward region decline with latitude at SKT and GHB, and reverse to positive at FHB and NAQ. These data suggest the presence of additional equivalent currents which are directed poleward at GHB, SKT, and SFT, and equatorward at FHB and NAQ.

4.1.4 Other substorm indicators

Fig. 4.4 provides a plot of other parameters which give information on the nature and timing of the disturbance. The first three panels show H component data from the lower-latitude magnetometer stations (green in Fig. 4.1b) which have been band-pass filtered between 20-200 s to exhibit signals in the Pi2 band. Station NAQ, which is directly equatorward of the main substorm-disturbed region, detects a large amplitude Pi2 starting at 0044 UT, confirming the determination of the onset time of substorm expansion. To the east and west, FAR and PBQ both see Pi2s of smaller amplitude shortly afterwards, indicating the large scale response to the substorm disturbance.

The lower panels of Fig. 4.4 show data from geostationary spacecraft, whose ionospheric footprints are shown by the coloured triangles in Fig. 4.1b. These have been mapped from geostationary orbit using the T-89 model for Kp = 2 (Tsyganenko, 1989). This is the Kp value prevailing during the interval 0000-0300 UT. The red triangles show the positions of the LANL spacecraft, LANL-97A and 1994-084. Panels four and five show energetic
Figure 4.4 The upper three panels show filtered (20-200 s) H-component magnetic field measurements from the low-latitude magnetometer array (green dots in Fig. 4.1b) for the interval 0020-0140 UT on 2 December 1999. Panels three and four similarly show geostationary electron fluxes in two energy channels (50-75 keV and 75-105 keV) from the SOPA instruments on the LANL-97A and 1994-084 spacecraft, while the bottom three panels show geostationary magnetic field measurements from the GOES-8 spacecraft in GSM co-ordinates. The dashed curves on the GOES-8 plots show the T-89 model magnetic field for Kp=2. The vertical dashed lines are as in Fig. 4.2.
electron data from LANL-97A and 1994-084, respectively. Both observe relatively weak dispersed injection signatures 10-20 min after substorm onset, consistent with their dawn sector location (see Fig. 4.1b) (Reeves et al., 1991). No significant ion injections were observed.

The blue triangle on Fig. 4.1b shows the footprint of GOES-8, located (at ~0100 UT) in the pre-midnight sector just to the west (and equatorward of) the main substorm disturbed region. The black solid line shows the mapped orbit of this spacecraft. The bottom three panels show GOES-8 magnetic field data in GSM coordinates. At the time of the substorm, GOES-8 was located at ~2000 MLT, ~1 h MLT to the west of the disturbed region, as indicated in Fig. 4.1b. The dashed curves show model magnetic field values derived from the T-89 Kp=2 model (Tsyganenko, 1989). Both B_x and B_y components follow the model field closely, while B_z displays a clear increase in magnitude starting at 0105 UT, which subsequently increases during the recovery phase to values well in excess of the model. This is likely due to the return of magnetic flux from the tail to the inner magnetosphere as a consequence of the substorm.

4.1.5 SuperDARN measurements of convection velocities

Turning now to consider the SuperDARN data, Fig. 4.5 shows line-of-sight velocity data from the selected radar beams indicated by the red lines in Fig. 4.1a. In the top panel the H component data at GHB is also shown, as an indicator of simultaneous magnetic activity. The vertical dashed lines are as in previous figures.

As illustrated in Fig. 4.1a, the Goose Bay radar observed the pre-midnight substorm sector during the interval of the disturbance. Data from beam 1, shown in the second panel of Fig. 4.5, clearly indicate a change in both direction and magnitude of the flow shortly after expansion phase onset. Before onset, the radar observed flows of ~100 m s^{-1} towards the radar (green) above ~72°, reversing to ~500 m s^{-1} away from the radar (orange) below that latitude. This is indicative of the pre-midnight flow reversal boundary lying within the
Figure 4.5 SuperDARN line-of-sight velocity measurements from the radar beams indicated in Fig. 4.1a are shown for the interval 0020-0140 UT on 2 December 1999. In the top panel the H-component magnetic field measured by the GHB magnetometer is also shown for purposes of comparison. The vertical dashed lines are as in Fig. 4.2.
field-of-view during this time. At the onset of the expansion phase, the poleward region of backscatter abruptly disappeared, indicative of enhanced precipitation within the field-of-view. It was mentioned above that a reduction in backscatter coverage due to D-region absorption is a common feature of the expansion phase. Fortunately, however, the equatorward region of backscatter remained, and reveals a remarkable change in the flow which developed in concert with the substorm bay at GHB. Within ~4 min (two radar cycles) of the onset, the flow below ~73° changed to become strongly towards the radar (deep blue and purple) with line-of-sight speeds in excess of ~1000 m s\(^{-1}\). These flows continued during the expansion phase until 0106 UT, when, in conjunction with the start of the recovery phase, the backscatter coverage became significantly reduced along the whole beam. When partial coverage was resumed, at ~0112 UT, the line-of-sight flows were much reduced, and a flow reversal boundary was again present within the field-of-view after ~0120 UT.

Related effects can be seen in the data from Goose Bay beam 8, shown in the third panel of Fig. 4.5. Here the line-of-sight flow is towards the radar along almost the whole beam prior to the beginning of the expansion phase. At onset, the backscatter coverage is again reduced in the poleward region. In the equatorward region, the line-of-sight flow intensified over the initial ~6 min as the bay developed at GHB, and reached ~1000 m s\(^{-1}\) after ~0054 UT. In this case, however, recovery saw an expansion in the region of backscatter, such that the changes in flow can be followed more fully. The flow remained towards the radar along most of the beam, and showed a rapid reduction to smaller values in approximate concert with the decline in the bay amplitude.

Turning to the data from Kapuskasing beam 8, located in the dusk sector (Fig. 4.1a) and shown in panel four, it can be seen that prior to onset, the line-of-sight flow below ~75° is away from the radar, becoming weaker and directed towards the radar at higher latitudes. Referring to Fig. 4.1a, it seems evident that these flows relate to the sunward and poleward flows of the normal twin-cell pattern in the dusk sector below ~75°, and to the flow-reversal boundary and polar cap at higher latitudes. After expansion onset a similar pattern
Chapter 4  Excitation of twin vortex flow during an isolated substorm

remained, but with the flow gradually strengthening over ~10 min as the substorm developed. It then declined again over ~10 min after the onset of recovery. Thus flow effects are also observed in the dusk sector outside the immediate vicinity of the substorm-disturbed region, which are inferred to be associated with an enhancement of the twin-cell pattern. It is also notable that no significant drop-out in backscatter was observed in this sector, but (with the exception of a small loss at ~72°) was rather enhanced in this case. Similar comments apply to the dawn sector data from Finland beam 8 (see Fig. 4.1a) shown in the bottom panel. Here flows are initially weak with limited backscatter evident at higher latitudes. However, the expanded coverage available during the expansion phase shows a strong poleward flow away from the radar above ~75° after ~0054 UT, which declined over ~10 min during recovery. It will become apparent below that this flow was also connected to the 'return' flow of a twin-vortex pattern that is generated and enhanced during the substorm expansion.

In order to visualize the flows from all six radars, Fig. 4.6 presents convection maps derived using the 'Map-Potential' algorithm discussed in Chapter 3. Each map corresponds to one 2 min radar experiment cycle time, and alternate maps are shown over the interval 0032–0118 UT spanning the substorm. These are grouped into three sets of four maps each, which correspond to the pre-onset interval, the expansion phase, and recovery. Fig. 4.6a thus displays the convection patterns observed between 0032 and 0046 UT, corresponding to the time leading up to and spanning the substorm expansion phase onset at 0044 UT. During this interval, and for some ~20 min prior to it, the IMF had been directed consistently northward, with a larger negative B_y component (see Fig. 4.2a and the icon at the bottom right-hand corner of the flow maps). A reasonably steady and well-defined twin-vortex flow was present during the interval, with a derived transpolar voltage $V_{pc}$ of ~40 kV (given in the bottom left-hand corner of each plot). Since backscatter was present nearly continuously between the extrema in the voltage values (as can be seen from the coverage of the plotted vectors), these voltages probably represent good estimates of the true values. Asymmetries in the flow pattern are evident during the interval, most probably associated with the negative IMF B_y conditions prevailing. Examination of the whole data
Figure 4.6a Streamlines and vectors of the ionospheric flow derived from the six-radar SuperDARN velocity measurements are shown on a geomagnetic grid, obtained from the 'Map-Potential' algorithm (see Chapter 3). The interval displayed here is 0032-0046 UT on 2 December 1999. Four maps are shown, corresponding to every other 2 min radar experiment cycle. Indicated at the bottom of each map is the total transpolar voltage $V_{PC}$ (left-hand corner), and the direction and magnitude (in the Y-Z plane) of the IMF (right-hand corner). In the top right-hand corner is the flow model employed to stabilise the potential solution in regions where no data are available, obtained from the statistical study of Ruohoniemi and Greenwald (1996).
set after \( \sim 0010 \) UT shows the flow emanating from the polar cap generally swinging dawnward as the auroral zone is approached on the nightside, and then duskward within the nightside auroral zone, to form a crescent-shaped nightside flow cell (the ‘dusk’ cell) spanning the midnight sector. During the interval shown in Fig. 4.6a, however, the flow in the post-midnight ‘tip’ of the crescent appears to have broken into a separate clockwise vortex (centred at \( \sim 70^\circ \) latitude and \( \sim 0300 \) MLT), possibly caused by inhomogeneous reconnection rates in the pre-onset tail. The last map in Fig. 4.6a spans the 2 min interval immediately following the onset of expansion at 0044 UT. Some conflicting flow vectors are evident at \( \sim 23 \) MLT, possibly indicative of some small scale electrodynamics which are not compatible with the derived potential pattern. However, in general it shows little change compared with the previous three maps, or indeed those of the previous \( \sim 20 \) min.

Fig. 4.6b shows the situation between 0048 and 0102 UT, corresponding to the expansion phase of the substorm. Here we see the immediate presence of a band of fast equatorward flow in the pre-midnight sector, as noted above in the Goose Bay data. The longitudinal width appears to be \( \sim 1.5 \) h MLT, from \( \sim 2100 \) to \( \sim 2230 \) MLT, as determined from the available radar coverage. A smaller enhancement of equatorward flow also occurred in the post-midnight sector, together with a distinct ‘zone of avoidance’ of the flow streamlines (i.e. a region of relative stagnation) in the immediate pre-midnight sector, centred near \( \sim 70^\circ \). This zone corresponds to the brightest region of auroral enhancement during the substorm, as will be seen below. Towards dawn and dusk, growing ‘return’ flows are also seen, associated with the line-of-sight velocity enhancements observed by the Kapuskasing and Finland radars noted above. Overall it is seen that a twin-vortex flow system is excited in the nightside ionosphere during the expansion phase, with foci lying at \( \sim 2000 \) MLT in the pre-midnight sector and at \( \sim 0100 \) MLT in the post-midnight sector, at a latitude of \( \sim 73^\circ \). The overall transpolar voltage associated with the flow grew from 37 kV at onset to peak at 80 kV at 0100 UT. The excited flows extend into the dawn-dusk and dayside sector, where the flow reversal boundary also appears to undergo a small simultaneous latitudinal contraction. On the dusk meridian, for example, where the boundary is relatively well-
Figure 4.6b As Fig. 4.6a but for the interval 0048-0102 UT.
Figure 4.6c As Fig. 4.6a but for the interval 0104-0118 UT.
defined, a poleward displacement of ~1° is evident in Fig. 4.6b. This motion will be investigated further below.

Fig. 4.6c shows the transition to the recovery phase, between 0104 and 0118 UT. In the first map, 0104-0106 UT, the equatorward flows in the pre-midnight sector had already decreased significantly, with $V_{PC}$ correspondingly reducing to 57 kV. Over the next ~10 min, the flows continued to diminish rapidly, and while remaining essentially similar to those occurring before the substorm, became more structured and variable.

4.1.6 VIS UV Earth camera auroral images and magnetic disturbance vectors

Exactly how the flows described above relate to the substorm aurora, and to the magnetic disturbance (in so far as the latter can be determined from the ground station coverage) is discussed below. Fig. 4.7 shows auroral images obtained by the VIS Earth camera, on which SuperDARN flow vectors and ‘Map-Potential’ streamlines have been superposed (black), together with pseudo-flow vectors obtained from ground magnetic observations (red). Each UV image corresponds to a 32.5 s integration, and each of the images obtained are shown at intervals of ~5 min, spanning the substorm. The SuperDARN map corresponds to the 2 min interval into which the centre time of the UV image falls. The magnetic data have been averaged over the same 2 min intervals as the SuperDARN scans, and thus correspond similarly to the UV image.

In deriving the magnetic vectors, it has been assumed that the perturbations are due to overhead Hall currents, and have thus been rotated anti-clockwise through 90° to point in the direction of the inferred flow. If this assumption is valid, the vectors should be aligned with the radar vectors, the ratio of their lengths being determined by the local height-integrated Hall conductivity. For the scales chosen in the figure, the two vectors would have equal length for a height-integrated conductivity of ~1.6 mho (no correction having been made for ground induction effects). In order to obtain useful results, baseline values have to be carefully chosen for each magnetometer station. Examination of the records
indicates that after the substorm, the magnetosphere returned to a quiet state during an extended interval of northward IMF (see Fig. 4.2a). Those stations for which a quiet-time baseline is routinely determined (e.g. the Greenland chain) were found all to have returned close to that baseline by ~0400 UT. Consequently, for simplicity and consistency a baseline has been chosen for all stations as the field measured at 0400 UT. This is also the baseline used in all plots of unfiltered magnetic data displayed in this chapter.

Fig. 4.7a begins by showing two UV images corresponding to the interval before expansion phase onset, centred at 0033:16 and 0037:47 UT. The UV auroras form an essentially continuous band circling the pole, reaching ~70° on the nightside and ~80° on the dayside, and being wider and reaching to higher latitudes at dawn compared with dusk. The latter asymmetry is likely associated with the negative IMF By conditions prevailing. Peak emission intensities are ~5 kR, near to midnight. Comparison with the flow vectors shows that in the region of SuperDARN radar coverage, the auroras lie in a region of westward flow located equatorward of the flow reversal boundary. Due to the (IMF B_y-related) asymmetry in the flow pattern, this statement applies continuously from the afternoon sector at ~1500 MLT, through dusk and midnight, to the post-midnight sector at ~0400 MLT. Throughout this sector, the poleward boundary of the auroras lies ~1°-2° equatorward of the flow reversal boundary, the latter being a reasonable initial proxy for the open-closed field line boundary. It is also notable that while substantial equatorward-directed flow is clearly present on the nightside during the pre-onset interval, the locations of neither the flow reversal boundary nor the auroras change significantly. If we take the pre-midnight sector, for example, the equatorward flow at ~70° latitude (near the flow reversal and auroral boundaries) is typically ~300 m s⁻¹. At this speed, the boundaries would move equatorward by ~5° of latitude in the ~30 min prior to substorm onset if they moved with the flow (i.e. if the boundaries were adiabatic). This is not the case. Examination of the data from the beginning of the day shows that the boundaries move less than ~1° during this interval. Consequently, one would conclude that the plasma flows through essentially steady-state nightside boundaries during this period. It is thus inferred that essentially steady nightside reconnection was in progress at a rate of ~40 kV during the pre-onset period, presumably
Figure 4.7a
Figure 4.7b
Figure 4.7c
Figure 4.7d
Figure 4.7e
Figure 4.7a-e Maps of the UV auroral luminosity projected onto a geomagnetic grid, are shown spanning the same interval as in Fig. 4.6. SuperDARN 'Map-Potential' streamlines and flow vectors are superposed. Magnetic data, shown red, are horizontal magnetic perturbation vectors which have been rotated anti-clockwise through 90° to point in the direction of the ExB drift, assuming they are due wholly to overhead Hall currents. Also indicated on the maps is the derived total transpolar voltage and the direction and magnitude (in the Y-Z plane) of the IMF, as in Fig. 4.6. The time indicated on each plot corresponds to the centre time of the 32.5 s integration interval of the UV image. The superposed SuperDARN and 2 min averaged magnetic vectors correspond to the interval shown in brackets, which encompasses the centre time of the UV image.
driven by continuous dayside reconnection with the $B_y$-dominated IMF. This situation contrasts with the usual 'growth phase' scenario in which the polar cap and auroral zone expand prior to expansion phase onset, as a consequence of unbalanced magnetopause reconnection (McPherron, 1970). Examination of the pseudo-flow magnetic vectors in Fig. 4.7a shows that they are quite small, but nevertheless often in reasonable agreement with the direction of the SuperDARN flows (though counter-examples are also evident). Comparison of the lengths of the vectors in the auroral region suggests Hall conductivities of ~1-2 mho.

Fig. 4.7b similarly displays two images which span the onset of the expansion phase at 0044 UT, these being centred at 0043:41 and 0048:12 UT, respectively. Comparing these with Fig. 4.7a shows that the aurora has brightened in the midnight sector to ~15 kR and then to ~25 kR, and has also expanded poleward by ~3° to form a well-defined substorm 'bulge' in the local time sector between ~2000 and ~0100 MLT. The 'bulge' thus sat directly between the 'foci' of the developing nightside twin-vortex flow pattern, though the development of the latter in the morning sector was somewhat obscured by the continuing clockwise vortex. The rapid poleward motion of the auroras, taking place in concert with strong and increasing equatorward flow, argues for the occurrence of rapid tail reconnection during this interval. Another feature of note is the 'zone of flow avoidance' mentioned above, which developed in the flow pattern at ~0048 UT, and was centred near ~70° in the immediate pre-midnight sector. This zone clearly relates to the blob of brightest auroral emission which lay between ~65° and ~70° in this sector. It is inferred that the flow was diverted around this region due to the high electrical conductivity resulting from the precipitation. Similar effects have been found in previous studies by Kirkwood et al. (1988), Morelli et al. (1995), Yeoman et al. (2000), and Khan et al. (2001). Looking now at the magnetic observations, and identifying the west coast Greenland stations which lay within the meridian of the substorm bulge (see Fig. 4.1b), it can be seen that the peak disturbance occurred (at station GHB) in the weak-flow region at the poleward border of the auroral emission. The relative lengths of the magnetic and flow vectors in this region indicate Hall conductivities of ~10-20 mho, assuming no breakdown of Fukushima's
theory. It can also be seen from the magnetic vectors that the westward electrojet spanned \(\sim 70^\circ - 73^\circ\) at this time (stations GHB to STF on the Greenland west coast chain, see Fig. 4.3a), and thus spanned, and extended poleward of, the poleward border of the UV emission. Significant magnetic effects were also observed at station IQA lying just poleward of the emission at \(\sim 2100\) MLT (see Figs. 4.1b and 4.2b). No magnetic vectors are shown directly within the ‘blob’ of strongest UV emission. The only station lying directly within this region was Greenland east station AMK (see Fig. 4.1b), which observed the largest negative \(H\) perturbation globally during the substorm, as previously shown in Fig. 4.2b. Unfortunately, however, the total horizontal disturbance at AMK cannot be shown because the \(D\) component is unavailable for this station for this interval.

Fig. 4.7c shows auroral images centred at 0054:06 and 0058:37 UT which span the interval of maximum observed magnetic disturbance, at \(\sim 0055\) UT. Here we see that the substorm auroral bulge had also reached its maximal extent, with the westward electrojet continuing to span and extend poleward of its poleward boundary. Unfortunately there are now no radar flow vectors within the electrojet region which can be compared with the magnetic vectors, and from which conductivity estimates can be made. The flow excited during the substorm is well-established, with \(V_{pc} \sim 70\) kV. Within the bulge, the ‘zone of avoidance’ near midnight is still evident. Outside the bulge, the enhanced ‘return’ flows are seen to extend via dusk and dawn into the dayside hemisphere. Associated magnetic disturbances of modest amplitude are thus produced in the surrounding regions where the conductivity is sufficient to produce a measurable effect.

Fig. 4.7d shows images, centred at 0104:32 and 0109:02 UT, which span the start of the substorm recovery phase at \(\sim 0106\) UT. During this interval the peak auroral intensities within the ‘bulge’ had diminished significantly to \(\sim 5\) kR, similar to values occurring before onset. However, comparison of the spatial distribution of the aurora with that shown in Fig. 4.7a shows that a small general poleward displacement of the poleward border of the aurora had occurred, by \(\sim 1^\circ - 2^\circ\), even on the dayside. This displacement mirrors the \(\sim 1^\circ\) poleward motion of the flow reversal boundary at dusk noted above. The magnetic
disturbance produced by the westward electrojet at the poleward border was still large, but diminishing, while the magnetic disturbance in the dawn sector had grown to become comparable in intensity. The transpolar voltage associated with the flow also diminished over this interval to pre-onset values.

Fig. 7e finally shows two recovery phase images, centred at 0114:57 and 0119:27 UT. Here the intensity of the ‘bulge’ had diminished still further, as had the currents and flows. Nonetheless, equatorward flow persisted across the poleward boundary of the auroras in the pre-midnight sector, suggestive of continuing reconnection in the pre-midnight tail. The transpolar voltage values were typically ~35 kV, a little less than those occurring before the substorm.

### 4.1.7 Summary of observations

Fig. 4.8 presents a summary of the main observations, from which the simple, yet unequivocal conclusion that flow was excited in the nightside high-latitude ionosphere by an isolated substorm, can be drawn. The top three panels remind us of the nature of the IMF (lagged by 74 min) during the substorm, with $B_x$ small and negative, $B_y$ large and negative, and $B_z$ intermediate in strength and positive. Such interplanetary conditions would be expected to result in modest, steady, convection velocities in the ionosphere, resulting from reconnection with the $B_y$-dominated IMF. In fact, under these conditions the Ruohoniemi and Greenwald (1996) statistical model predicts a transpolar voltage of 33 kV. Flows associated with transpolar voltages up to ~80 kV, as observed, cannot reasonably be accounted for on this basis. In addition, there are no indications in the dayside auroral data of major magnetopause dynamics during the interval. The fourth and fifth panel summarises the ground magnetic data, emphasising that the disturbance studied has the typical characteristics of an isolated substorm of modest duration and amplitude. Overall, the bay lasted for ~25 min, had a peak amplitude of ~250 nT in the $H$ component, and was preceded by a well-defined Pi 2 signal. Weak energetic particle injections and field strength increases were also observed at geostationary orbit, as shown above. The sixth panel in
Figure 4.8 Summary plot of the principal observed substorm features. The top three panels show the IMF measurements by the ACE spacecraft in GSM co-ordinates, lagged by 74 min as in Fig. 4.2a, shown for the interval 0020-0140 UT on 2 December 1999. The fourth panel similarly shows the H-component of the magnetic field measured by the GHB magnetometer, while the fifth panel shows the H-component magnetic field band-pass filtered between 20 and 200 s measured by the NAQ magnetometer. The sixth panel shows the total transpolar voltage $V_{PC}$ derived from SuperDARN radar data using the 'Map-Potential' algorithm, while the seventh panel shows an estimate of the latitude of the flow reversal boundary on the dusk meridian, obtained from the minimum in the electrostatic potential. The horizontal dashed lines show the location averaged over 20 min intervals before and after the substorm. The vertical dashed lines are as in Fig. 4.2.
Fig. 4.8 shows the total transpolar voltage. It seems obvious that the excitation of flow relates directly to the interval of substorm expansion, both in terms of the times of increase and decay. Finally, the seventh panel shows the latitude of the flow reversal boundary on the dusk meridian where it is well-defined, determined from the minimum in the voltage of the ‘Map-Potential’ fit. Since the solution for the potential is obtained on a discrete latitudinal grid of 1° resolution, these data are rather marginal for the present purpose. However, as indicated above, they suggest that a small poleward displacement of the boundary took place during the substorm. Averaged over the ~20 min intervals before and after the substorm, indicated by the horizontal dashed lines, the boundary moved from ~77° before to ~78° after, i.e. a displacement of ~1°. The poleward motion of the flow reversal boundary is also evident in the line-of-sight data from beam 8 of the Kapuskasing radar shown in Fig. 4.5 panel four, although the latitude of the boundary is somewhat lower due to the later MLT.

A few further comments are in order concerning the $V_{PC}$ estimates shown in Fig. 4.8 (and in Figs. 4.6 and 4.7). The first concerns the sensitivity of the results to the statistical flow model employed to stabilize the spherical harmonic solutions in regions where radar data are sparse, as mentioned in Chapter 3. This question has been examined quantitatively by re-deriving the voltage estimates using different fixed Ruohoniemi and Greenwald (1996) models appropriate to various IMF conditions. The voltages derived typically vary by only a few kV from those shown in Fig. 4.8, such that it is clear that the above results depend principally on the radar data, and not upon the statistical model. This may be expected from the fact that the radar data generally adequately span the region between the foci of the flow cells as mentioned above. The importance of continuity of radar data coverage to the voltage estimates is emphasised by the results of a second investigation, in which the radar data which show the equatorward surge in the substorm sector (specifically the Goose Bay data) have been removed prior to employing the ‘Map Potential’ algorithm. In this case the voltage determinations before and after the substorm are at similar levels to those displayed in Fig. 4.8. However, during the substorm itself, the voltage peak seen in Fig. 4.8 is entirely missing. Good continuity of radar data coverage across the substorm-disturbed region is
thus essential for adequate estimation of the voltages associated with the flow and their variation during the substorm.

### 4.2 Reconnection rates analysis

The following discussion of the physical origins of the flow excitation, is based on the ideas introduced in Chapter 2 of Siscoe and Huang (1985), Cowley and Lockwood (1992), and Cowley et al. (1992, 1998), in which it is presumed to be due principally to an interval of enhanced reconnection and net open flux closure in the tail. Here estimates of the reconnection rates involved, and of the net flux closure, are made on this basis.

It was pointed out above that in the period prior to expansion onset the steady nature of the flow and precipitation boundaries indicates that this was an interval of quasi-steady balanced dayside and nightside reconnection. In this case, the mean reconnection rates are approximately equal to the polar cap voltage, so that averaging the SuperDARN voltage data over the 20 min interval prior to expansion onset at 0044 UT yields estimates of the pre-onset reconnection rates (dayside and tail) of $43 \pm 4$ kV (mean and standard deviation). In the interval after the substorm, specifically over the period 0108-0128 UT, we similarly find that the average polar cap voltage was $33 \pm 5$ kV. These values indicate that the system was being driven by quasi-steady dayside reconnection at a mean rate between 30 and 45 kV before and after the substorm, and that this was matched by tail reconnection at similar mean rates during these periods. During the substorm, however, it is suggested that the tail reconnection rate was temporarily elevated above such values, while it seems most reasonable to suppose that dayside reconnection continued at similar rates of 30-45 kV. In support of the latter assumption, it is noted that the interplanetary conditions which are primarily deterministic of the dayside reconnection rate did not change significantly over the interval (e.g. Fig. 4.8), nor is there any evidence of major dayside dynamics in the auroral data (Fig. 4.7). If this is correct, then a net destruction of open flux would be expected to have taken place during the substorm, associated with a contraction of the open-
closed field line boundary. Evidence for such contraction, though incomplete, is indeed present in the data. Specifically, it was previously noted that the flow reversal boundary in the dusk sector, where it is most sharply defined, underwent a poleward displacement of ~1° (Figs. 4.5-4.8), near the limit of resolution of the SuperDARN data. It is also evident that a poleward contraction of ~1°-2° took place in the poleward boundary of the UV auroras at most local times (Fig. 4.7), though the relationship to the motion of the open-closed field line boundary remains somewhat uncertain. Thus while evidence for contraction exists, its value (of order ~1°) is imprecisely defined by the data available. The analysis presented below is tailored to accommodate the imprecision in this parameter.

The physical scenario on which the calculation is based is illustrated in Figs. 4.9 and 4.10, where only the principal features are shown, and not details specific to the interval considered here, such as the IMF \( B_y \)-related asymmetries in the flow, or the details of the ‘flow suppression’ effects. In order to set the theoretical scene, first consider the system response to a short-lived pulse of tail reconnection, as shown in Fig. 4.9. In this diagram the instantaneous open-closed field line boundary is shown by the heavy solid line, while the plasma streamlines are shown by the lighter arrowed lines. For simplicity, it has been assumed that the initial equilibrium open-closed field line boundary is circular in shape, and that a pulse of tail reconnection has caused a poleward displacement of the boundary in the nightside sector. The flux tubes immediately equatorward of the ‘bulge’ have thus been newly reconnected in the tail, and have been added to the closed flux tube region in the nightside magnetosphere. This perturbs the system from equilibrium, and excites flow which transports flux from the nightside, around the Earth and towards the dayside, thus forming part of the Dungey cycle. In the ionosphere, this transport is manifest as a twin-vortex flow, which is such that the open-closed field line boundary is carried equatorward in the region of the nightside bulge, and poleward elsewhere. These motions thus return the boundary towards an equilibrium circular shape with a reduced amount of open flux present, shown by the dashed circular line, after which the flow dies away. In effect, the action of the flow is to distribute the newly closed flux in the system approximately uniformly around the open-closed field line boundary.
Figure 4.9 Schematic of the flow which is excited by a single short-lived pulse of nightside reconnection. The instantaneous open-closed field line boundary is shown by the heavy solid line, while the plasma streamlines are shown by the lighter arrowed lines. The implied boundary motion is illustrated by the large arrows, and the equilibrium boundary position is indicated by the dashed circle.
Figure 4.10 Sketch showing idealised boundary motions and plasma streamlines (a) before, (b) during, and (c) after the substorm studied here, such that (a) and (c) correspond to quasi-steady states, while (b) corresponds to an interval in which the tail reconnection rate is enhanced and exceeds the dayside rate. The heavy lines show the position of the open-closed field line boundary, which is shown solid in the adiabatic portions and dot-dashed in the region of the nightside merging gap. The large arrows in (b) show the motion of the boundary after the enhancement of tail reconnection rate has taken place, while the dotted line in (b) and (c) shows the initial position of this boundary for ease of comparison. The lighter arrowed lines show the plasma streamlines.
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The more general situation is illustrated in Fig. 4.10, where the effect of a more extended interval of enhanced tail reconnection is shown, which takes place in the presence of steady dayside reconnection, such as has been inferred here. Fig. 4.10 (a) shows the situation in the interval of quasi-steady flows which occurred before substorm expansion onset. The heavy line represents the open-closed field-line boundary, with the dot-dashed portion being the ‘merging gap’ mapping to the nightside reconnection region. The lighter arrowed lines represent the plasma streamlines, which thus cross the boundary only in the region of the merging gap, while being aligned with the boundary in the ‘adiaroic’ regions outside. Fig. 4.10 (b) corresponds to the expansion phase of the substorm, in which tail reconnection closes open flux at an enhanced rate (larger than the dayside reconnection rate), such that the open-closed field line boundary now moves poleward as shown, beginning in the sector of the merging gap. The dotted line shows the previous location of the boundary for ease of comparison. As above, the implied departure of the system from equilibrium excites Dungey-cycle convection in the magnetosphere and twin-vortex flow in the ionosphere, which is such as to transport closed flux tubes away from the merging gap region of closure sunward to other local times. The open-closed field line boundary thus contracts everywhere, as indicated by the large arrows. In this situation the foci of the twin-vortex flow cells will lie approximately at the ends of the nightside merging gap as shown (and hence at the ends of the substorm bulge, as observed), separating the equatorward flow of plasma across the nightside merging gap from the poleward flow in the adiaroic boundary region outside. In this case, therefore, where the nightside reconnection rate exceeds the dayside rate, the ‘polar cap voltage’ determined from SuperDARN radar data will correspond essentially to the voltage across the nightside merging gap. Fig. 4.10 (c) shows the situation after the tail reconnection rate has declined once more and steady flows have been resumed. This occurs when the flux redistribution process is complete, such that (in the Cowley and Lockwood (1992) paradigm) the net closed flux is distributed approximately uniformly round the boundary, leaving the shape of the contracted boundary approximately unchanged.
In order to analyze this situation, specifically for the case of interest here where the
nightside reconnection rate exceeds the dayside rate, let the amount of open flux present in
the system as \( \Phi(t) \), associated with a polar cap area \( A(t) \), where \( \Phi(t) = B_j A(t) \), and \( B_j \) is
the polar magnetic field strength (taken to be constant for simplicity and equal to
60,000 nT). The dayside and nightside reconnection rates are then written as \( \Phi_d(t) \) and
\( \Phi_n(t) \), where by definition \( \Phi_d(t) \) is positive (associated with increasing open flux), and
\( \Phi_n(t) \) is negative (associated with decreasing open flux). The nightside reconnection rate
can then be written as

\[
\Phi_n(t) = -B_j \int_{s_1}^{s_2} (v_n(t) - v_B(t)) \, ds ,
\]  

(4.1)

where \( v_n(t) \) is the plasma velocity normal to the boundary (taken as positive when directed
equatorward), \( v_B(t) \) is the boundary velocity (defined only in the normal direction and
again taken as positive when directed equatorward), and \( ds \) is the line element along the
nightside merging gap of the open-closed field line boundary, from the dusk end of the line
\( (s_1) \) to the dawn end \( (s_2) \). The integrand in Eq. (4.1) simply represents the transport of
magnetic flux across the nightside merging gap in the latter’s rest frame, per unit length of
line. It is readily shown that the integral of the first term in Eq. (4.1) is

\[
B_j \int_{s_1}^{s_2} v_n(t) \, ds = V(s_2,t) - V(s_1,t) = V_{PC}(t) ,
\]  

(4.2)

where \( V(s_1,t) \) and \( V(s_2,t) \) are the electric potentials at either end of the nightside merging
gap, \( V_{PC}(t) \) is the total transpolar voltage (as obtained from SuperDARN data), and the
approximation holds when the nightside reconnection rate is larger than the dayside
reconnection rate, as noted above. The integral of the second term in Eq. (4.1) is just the
rate at which flux is swept out by the motion of the nightside reconnection line (i.e. the
merging gap), taken as positive for equatorward motion, so that we have

\[
\Phi_n(t) = -V_{PC} + B_j \frac{dA_{eq}}{dt} .
\]  

(4.3)
Integrating these quantities over an event of duration $\tau$, and denoting averages by angle brackets, we then have

$$\langle \Phi_n \rangle = -\langle V_{pc} \rangle + \frac{B_l \Delta A_{mg}}{\tau} , \quad (4.4)$$

where $\Delta A_{mg}$ is the total area swept out by the nightside merging gap during the event (positive for equatorward displacements). This equation thus determines the averaged nightside reconnection rate during an interval in terms of the mean polar cap voltage during the event and the displacement of the open-closed field line boundary in the region of the merging gap. The dayside reconnection rate is then given by the relation

$$\langle \Phi_d \rangle + \langle \Phi_n \rangle = \frac{B_l \Delta A}{\tau} , \quad (4.5)$$

where $\Delta A$ is the change in total area of the polar cap during the interval. Thus introducing Eq. (4.4) into Eq. (4.5) yields

$$\langle \Phi_d \rangle = \langle V_{pc} \rangle + \frac{B_l (\Delta A - \Delta A_{mg})}{\tau} . \quad (4.6)$$

Now let $\Delta A_{mg} = f_{mg} \Delta A$, such that the area swept out by the nightside merging gap is some fraction $f_{mg}$ of the total change in area of the polar cap. From Eqs. (4.4) and (4.6) we then finally have

$$\langle \Phi_n \rangle = -\langle V_{pc} \rangle + f_{mg} \frac{B_l \Delta A}{\tau} \quad \text{and} \quad \langle \Phi_d \rangle = \langle V_{pc} \rangle + (1 - f_{mg}) \frac{B_l \Delta A}{\tau} . \quad (4.7a,b)$$

Clearly if $\Delta A = 0$ for a particular interval then the magnitudes of the mean dayside and nightside reconnection rates are equal to each other, and equal also to the mean polar cap voltage $\langle V_{pc} \rangle$, as already noted above. On the other hand, if the polar cap area contracts during the interval such that $\Delta A < 0$, then the magnitude of the nightside reconnection rate will be greater than $\langle V_{pc} \rangle$, while that of the dayside reconnection rate will be less than $\langle V_{pc} \rangle$. An inconsistency occurs if the magnitude of the second term in Eq. (4.7b) exceeds
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the first, implying that \( \langle \Phi_d \rangle \) is negative, contrary to assumption. However, for the event analysed here a more stringent condition on \( \langle \Phi_d \rangle \) can be considered, since it has been argued above that the dayside reconnection rate probably remained in the range 30-45 kV during the substorm, and this is therefore imposed as a condition.

Eqs. (4.7a) and (4.7b) are now used to estimate the reconnection rates during the substorm expansion phase. If we examine these equations it is clear that some of the parameters on the right hand sides are determined by the data better than others. In particular, the mean polar cap voltage \( \langle V_{pc} \rangle \) during the intervals is reasonably well determined from the SuperDARN data, accepting the above interpretation of this quantity. On the other hand, the net area swept out by the open-closed field line boundary \( \Delta A \) and the fraction \( f_{mg} \) of that associated with the nightside merging gap are not so well determined. With regard to \( f_{mg} \), values can be estimated on the assumption that the effect of the flow is to redistribute the newly closed flux uniformly around the open-closed field line boundary, as in the Cowley and Lockwood (1992) paradigm. In this case \( f_{mg} \) will also represent the fraction of the length of the open-closed field line boundary that is occupied by the nightside merging gap, and this can be estimated from the flow patterns during the expansion phase. It has been shown above that the maximum and minimum in the electric potential will lie at either end of the nightside merging gap when the tail reconnection rate exceeds the dayside rate as occurs here. Identification of the location of the foci of the flow cells thus provides an indication of the magnetic local time extent of the merging gap, from which \( f_{mg} \) can be estimated. Examination of the flow maps during the expansion phase in Figs. 4.6 and 4.7 suggests \( f_{mg} \sim 0.3 \), and a likely range \( f_{mg} = 0.2-0.4 \) is therefore employed. With regard to the change in polar cap area, it was only possible to make one approximate determination of the poleward displacement of the boundary, by \( \sim 1^\circ \) latitude in the dusk sector where a clearly-defined flow reversal is evident. The approach has therefore been to look carefully at the sensitivity of the results to these less-well determined parameters.

In effect, what has been done is to plot contour maps of \( \langle \Phi_s \rangle \) and \( \langle \Phi_d \rangle \) determined from Eq. (4.7) on the \( f_{mg} - \Delta A \) plane, and to delineate regions of consistency both with the rather
roughly-obtained limits on these latter parameters, and on $\langle \Phi_d \rangle$ as discussed above. However, rather than use $\Delta A$ directly, the latitude displacement of the boundary in the dusk local time sector has been used instead. From this displacement the areas $\Delta A$ have been calculated by extrapolation of the initial and final boundary positions to other local times. For simplicity (and in accordance with the Cowley-Lockwood paradigm) it has been assumed that the initial and final boundaries are circles drawn about a common centre. The position of the appropriate centre has been judged from the shape of the flow patterns and auroral boundaries, and has been chosen on this basis to be displaced from the magnetic pole by 4° of magnetic latitude along the 22 MLT meridian. The displacement of the 'centre' towards the nightside accommodates the usual day-night asymmetry in the position of the boundary, while the displacement towards dusk is suggested by the corresponding dawn-dusk asymmetry in the auroral boundary and is associated with the prevailing sense of IMF $B_y$ (negative). Examination of the flow and auroral patterns overall indicates that this is a very reasonable choice, and that no substantial improvement would result from attempting to use some more complex boundary shape.

Results are shown in Fig. 4.11, averaged over the interval of enhanced convection, i.e. over 0044-0108 UT (Fig. 4.8). For this interval it is found that $\langle V_{PC} \rangle = 59\text{kV}$ from the SuperDARN data. Using this value reconnection rate contours have been plotted on the $f_{mg} - \Delta \Lambda_B$ plane, where $\langle \Phi_n \rangle$ and $\langle \Phi_d \rangle$ are shown by the solid and dashed lines, respectively. Parameter $f_{mg}$ is shown on the vertical axis, and the displacement in magnetic latitude of the dusk flow reversal boundary $\Delta \Lambda_B$ is shown on the horizontal axis. From the latter parameter the change in area of the polar cap has been calculated according to the above algorithm, starting from an initial boundary position at $\Lambda_B = 77^\circ$ (Fig. 4.8), so that $\Delta A$ becomes increasingly negative as we move from left to right across the plot. It is found that a $1^\circ$ poleward displacement of the boundary corresponds to a flux closure of $B_{d} \Delta A = -0.5 \times 10^8\text{ Wb}$, while $2^\circ$ corresponds to $-0.9 \times 10^8\text{ Wb}$. At the left-hand edge of the plot we have $\Delta \Lambda_B = 0$ (and $\Delta A = 0$), so that at this limit Eqs. (7a) and (7b) give $\langle \Phi_d \rangle = -\langle \Phi_n \rangle = \langle V_{PC} \rangle$, as discussed above. We also have $\langle \Phi_n \rangle = -\langle V_{PC} \rangle$ along the bottom edge of the plot where $f_{mg} = 0$, and $\langle \Phi_d \rangle = \langle V_{PC} \rangle$ along the top edge of the plot where...
Figure 4.11 Reconnection rate contours determined from Eq. (4.7) plotted on the $f_{mg}$-$\Delta \Lambda_B$ plane, where $f_{mg}$ is shown on the vertical axis, and the displacement of the magnetic latitude of the dusk flow reversal boundary $\Delta \Lambda_B$ during the substorm is shown on the horizontal axis. The solid lines show contours of the nightside reconnection rate obtained from Eq. (4.7a), while the dashed lines show contours of the dayside reconnection rate obtained from Eq. (4.7b). The dark-shaded area in the bottom right corner represents an area of inconsistent results in which the dayside reconnection rate becomes negative. The horizontal dotted lines mark the likely range of $f_{mg}$ values for the substorm, with the exterior region being shaded. Also shaded is the region of unlikely dayside reconnection rates lying outside the range 30-45 kV. The unshaded area corresponds to the region of solutions that conforms to both these constraints.
$f_{mg} = 1$. Away from these respective boundaries $\langle \Phi_a \rangle$ becomes increasingly negative as $f_{mg}$ and $\Delta \Lambda_B$ both increase, while $\langle \Phi_d \rangle$ drops to smaller values as $f_{mg}$ decreases and $\Delta \Lambda_B$ increases. Eventually $\langle \Phi_d \rangle$ becomes negative in the dark-shaded area in the bottom right corner of the plot, this representing an area of inconsistent results (as discussed above) when $(1 - f_{mg}) \Delta A$ becomes too negative.

Now consider the likely ranges of the controlling parameters, and the consequent likely range of values of the reconnection rates. First, as indicated above, the likely range of $f_{mg}$ was between $\sim 0.2$ and 0.4. This range is marked by the horizontal dotted lines, and the exterior region is shown shaded. Second, according to the above arguments, we can reasonably expect the dayside reconnection rate to have lain in the range $\sim 30$ to $\sim 45$ kV during the interval. The regions outside these limits are also shaded. It can be seen that these two conditions delimit an area on the plot which spans a range of $\Delta \Lambda_p$ between $\sim 0.5^\circ$ and $\sim 1.5^\circ$. This result is therefore completely consistent with the SuperDARN dusk boundary data, which indicate a poleward contraction by $\sim 1^\circ$, near the limit of resolution of the data. These latter observations do not, therefore, impose any further constraints in this case. The implication of the results in Fig. 4.11 is thus that the mean nightside reconnection rate during the substorm, averaged over the 24 min interval 0044-0108 UT, was $\sim 70$ kV, lying in the range $\sim 65$-$75$ kV. It is therefore possible to further estimate that the total magnetic flux closed in the tail during the substorm was $\sim 0.9 - 1.1 \times 10^8$ Wb, compared with $\sim 0.4 - 0.6 \times 10^8$ Wb which was opened on the dayside over the same interval. The net flux closed during the substorm was thus also $\sim 0.4 - 0.6 \times 10^8$ Wb, corresponding to a $\sim 1^\circ$ contraction of the boundary overall. It can also be estimated that the total amount of open flux present prior to substorm onset was $\sim 3 \times 10^8$ Wb, this representing an entirely typical value under general conditions, and for pre-substorm intervals in particular (Newell et al., 2001). Thus the net flux closed during the substorm represents $\sim 15$-$20\%$ of the total open flux present prior to onset.
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4.3 Summary

This chapter presents observations of the ionospheric flows which were excited in concert with the onset and decay of the expansion phase of an isolated high-latitude substorm of modest amplitude and duration. The flow was of twin-vortex form with foci on the nightside at either end of the substorm auroral bulge. The transpolar voltage associated with the flow increased from ~40 kV prior to onset, to peak at ~80 kV after 15 min, which was ~5 min after the peak in the magnetic disturbance. The flow then declined back down to ~35 kV over ~10 min in the recovery phase. During this interval the IMF remained steady, with $B_v \approx -9$ nT, and $B_z \approx +5$ nT. The flow enhancement (and substorm) is inferred to have resulted from a burst of reconnection in the pre-midnight plasma sheet.

The 'return' flows of the enhanced flow pattern extended widely on either side of the region directly affected by the substorm, over the polar cap, and into the dayside sector. The changed and enhanced flow pattern, combined with prevailing ionospheric conductivities, produced magnetic disturbances of modest amplitude over a large area surrounding the substorm-disturbed region. These data thus support the prior conclusions of Grafe et al. (1987) and Opgenoorth and Pellinen (1998), based principally on magnetic data from the dusk sector, that a prompt response in the global convection system often occurs at expansion phase onset. Opgenoorth and Pellinen suggested that the response could be produced by a suppression of the flow in the region of 'dipolarised' flux in the nightside magnetosphere, mapping essentially to the substorm bulge, resulting in a deflection of the surrounding flow around this region. Such deflection would give rise to a flow enhancement on either side of the bulge, but this effect alone would result in no change in the overall transpolar voltage. For the localised substorm studied here, however, it has been found that the principal effect was the excitation of 'new voltage' during the expansion phase, in which the total transpolar voltage increased by a factor of two.

Flow suppression within and deflection around the dipolarised region (the 'blob' of brightest auroral emission) occurred during the expansion phase, as observed in previous
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studies by Morelli et al. (1995), Yeoman et al. (2000), and Khan et al. (2001). However, in the present case the region effected was relatively small and localized near midnight, such that this represented a distinct but secondary effect. The main flow effect in this particular substorm was thus the overall enhancement mentioned above. The nightside reconnection rate averaged over the ~24 min of this enhancement is estimated to have been ~65-75 kV, compared with continuing dayside reconnection rates of ~30-45 kV. The net destruction of open flux during the substorm is thus estimated to have been $\sim 0.4 - 0.6 \times 10^8$ Wb, corresponding to ~15-20% of the open flux present at onset. The corresponding overall contraction of the open-closed field line boundary during the substorm was thus ~1° latitude, close to the resolution limit of the SuperDARN data.

The explanation which has been forwarded for the flow effect observed here, in terms of the contribution of tail reconnection and field dipolarisation to Dungey cycle convection, should hold for substorms in general. One may therefore expect that such flow excitation should be a common feature of substorm intervals. Factors which might mitigate against a clear identification of the effect in general cases include (a) variations in the direction and strength of the IMF during the substorm which produce additional modulations of the flow driven by magnetopause reconnection; (b) large-scale flow reconfigurations on the nightside due to flow suppression and deflection effects over larger areas of the substorm bulge; (c) dropout of radar backscatter from the crucial substorm-disturbed region due to ionospheric absorption; and (d) inadequate imaging of the flow pattern within the collective field of view of the radar array, which is limited both in local time and in latitude. The identification of the flow enhancement effect in the present data set clearly resulted from a rather fortunate combination of geophysical and operational circumstances. A future agenda is set, however, to search for related features in other substorms.
CHAPTER 5

Ionospheric flow during extended intervals of northward but $B_y$-dominated IMF

From the discussion in Chapter 2 it will be clear that the nightside ionosphere and geomagnetic tail for northward IMF is often anything but ‘quiet’, and is instead characterised by a wealth of flow and precipitation phenomena having a variety of characteristics. However, the relationships between many of these phenomena have not yet been clarified, and no overall picture has yet emerged of the behaviour of the tail and conjugate ionosphere under these conditions. This chapter aims to contribute to discussion of this issue through the study of SuperDARN radar observations of nightside flows and related parameters during two extended intervals in which the IMF clock angle remained relatively steady at intermediate values $\theta \sim -50^\circ$ to $-60^\circ$. Thus IMF $B_z$ was positive, but the largest transverse field component was IMF $B_y$, which was consistently negative. These intervals (on 02 and 14/15 December 1999) were sufficiently extended (~6 h each) that we may reasonably expect the magnetosphere to have reached a state entirely characteristic of those conditions, rather than e.g. being significantly influenced by prior intervals of differently-directed IMF. For these northward but ‘intermediate’ orientations of the IMF we may thus expect on the basis of the above discussion that open flux production at the magnetopause persisted at modest rates, and indeed it is shown below that IMF $B_y$-distorted twin-cell flow persisted throughout both intervals, with transpolar voltages typically in the range ~20-40 kV. We might also anticipate the excitation of ‘lobe’ convection cells on the dayside. However, because intervals with good radar coverage of the nightside hours have been chosen for study, coverage of the dayside flows is not extensive in these data. Thus the presence or absence of lobes cells is not well-determined by these data and does not form a major topic of discussion.
With regard to nightside phenomena, however, a significant question exists concerning the magnetospheric response to modest but steady dayside driving under these conditions. During the growth phase of substorms with the IMF directed southward, the transpolar voltage (and implied open flux input to the tail) is typically twice the above values (i.e. ~60-80 kV), and generally ~30-40 min elapses before reconnection and plasmoid formation is excited in the near-Earth tail at substorm expansion phase onset. We may then ask whether substorms occur with reduced frequency or with reduced amplitude under conditions of reduced but continuous driving? In fact it is shown in this chapter that no classic substorm features were observed at all during these long intervals. Instead, large-scale bursts of flow were observed in the nightside ionosphere, having recurrence time scales of ~1 h and lasting a few 10s of minutes. These properties suggest a connection with the flow phenomena previously described by de la Beaujardière et al. (1994) and Senior et al. (2002), and thus also, possibly, with BBF/PBIs. In this chapter these flow observations are examined in some detail, and the implications for the balance between open flux production at the magnetopause and closure in the tail during northward IMF intervals of intermediate clock angle are discussed.

### 5.1 Observations Overview: Interval 1 (0130 - 0730 UT 2 December 1999)

The ground and space observations made during the first of the two 6-hour intervals (2 Dec 1999) are discussed below. To begin with, an overview of the interplanetary data is given, followed by a more detailed look at the magnetic, flow, particle, and auroral data.

#### 5.1.1 Upstream interplanetary conditions

Interplanetary conditions during the interval were monitored by the ACE spacecraft (see Chapter 3), located upstream of the Earth at GSM coordinates \((X,Y,Z) = (222,21,-25)\) \(R_E\). Fig. 5.1 presents data from the MAG and SWEPAM instruments, lagged by 76 min to account for the propagation delay (as discussed in Chapter 4), for the 18 h interval from
Figure 5.1 Upstream interplanetary observations from the ACE spacecraft for 1930 UT on 1 Dec to 1330 UT on 2 Dec 1999, lagged by 76 min to account for the propagation delay to the ionosphere. The top two panels show solar wind density and velocity data (the dashed line represents data from Geotail, which was used where data were missing from ACE). The middle three panels show IMF data in GSM co-ordinates, and the bottom two panels show the field magnitude and clock angle. The clock angle is defined with respect to north, such that 0° corresponds to a transverse field purely in the +z direction (northward), ±90° to ±y (respectively) and ±180° to -z (southward).
1930 UT on 1 Dec to 1330 UT on 2 Dec 1999. This is an expanded interval describing the upstream interplanetary conditions for 6 h either side of the interval of specific interest, which is delimited by the vertical dashed lines. The top two panels show the solar wind proton number density \( n_p \) and speed \( v_p \) from ACE/SWEPAM. It should be noted that on 2 Dec no data were available from ACE/SWEPAM between ~0330 and ~0630 UT. Data from the Geotail CPI instrument (Frank et al., 1994) has therefore been used to give an indication of \( n_p \) and \( v_p \) during this period (indicated on Fig. 5.1 by the dashed lines). A negligible propagation delay existed between Geotail and the ionosphere, owing to Geotail's location at \((X,Y,Z) \approx (15,-20,2) \) \( \text{RE} \), consistent with features observed in both the ACE and Geotail data sets from before and after the ACE/SWEPAM data dropout. Before the data gap the density remained relatively constant at \( \sim 10 \text{ cm}^{-3} \) and the velocity between 330-380 km s\(^{-1}\). The Geotail data indicates a decrease in velocity of \( \sim 30 \text{ km s}^{-1} \) approximately coincident with the SWEPAM data drop-out.

The middle three panels show the GSM components of the IMF from ACE/MAG, with the magnitude and clock angle of the field shown in the bottom two panels. IMF \( B_x \) was near zero or positive throughout the main interval of interest, while \( B_y \) was large and negative, and \( B_z \) predominantly positive (and had been near zero or positive for more than 3 h previously). These values translate to a field strength (6th panel) which was nearly constant at \( \sim 10 \pm 1 \text{ nT} \), and a clock angle (bottom panel) which, for the most part (~0230-0630 UT), remained near \( \sim 60^\circ \). The mean value over the main interval was \( -59^\circ \), with a standard deviation of \( 17^\circ \).

5.1.2 SuperDARN flow data overview

Illustrated in Fig. 5.2, are the fields of view of the six northern hemisphere SuperDARN radars at the start and end times of the interval of interest, i.e. 0130 and 0730 UT. These are shown in the same format as in Fig. 4.1a. The fields-of-view of those radars from which line-of-sight data will be displayed below are shaded blue, namely, the Saskatoon, Kapuskasing, Goose Bay, and Iceland West radars. Data will be displayed from the beam
Figure 5.2 Fields-of-view of the six northern hemisphere SuperDARN radars at 0130 (top) and 0730 UT (bottom), the start and end times of the 02 Dec 1999 interval. These are plotted on a geomagnetic grid from the pole to 60°, with 12 MLT at the top and dusk to the left. Fields-of-view coloured blue are those of the four radars for which detailed line-of-sight measurements will be discussed, using the beams indicated in red.
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directions marked by the red lines. During the study interval, all six radars were operating in the same standard mode as before. It should be noted that the southern hemisphere data has also been inspected, however, backscatter coverage is so limited for the interval that these data do not form part of the following discussion.

Fig. 5.3 presents line-of-sight SuperDARN velocity data for the 6 h interval, from the five northern hemisphere radar beams mentioned above. These beams have been chosen for their good backscatter returns, as well as for their wide coverage of the nightside ionosphere. Immediately evident is the continuous flow observed over the entire interval, with speeds of $\sim 500-1000$ m s$^{-1}$. These flows are directed away from the radar at Saskatoon (beam 0) and Kapuskasing (beam 5) indicative of sunward 'return' flow in the dusk convection cell, towards the radar at Kapuskasing (beam 15) and Goose Bay (beam 6) indicative of antisunward flow over the polar cap into the auroral zone, and strong but variable (directed mainly east-west) at Iceland West (beam 8). There is also evidence of strong variability or pulsing in the flow, which is particularly marked, for example, at Goose Bay (beam 6). The vertical dashed lines indicate six such 'pulsed' features in the flow, the details and timing of which will be discussed below. It is immediately evident that this is an interval of dynamic and often high speed nightside flow.

In order to investigate the nature of the flow further, a sequence of convection maps have been derived from all the available northern hemisphere SuperDARN data using the Map Potential model. In this study, spherical harmonic fits which use terms up to sixth order are employed to fit the northern hemisphere data, the functions being expressed about a pole which has been shifted by 2° towards the nightside. A lower-latitude convection limit of 67° relative to this pole has also been imposed, as deemed appropriate for the contracted nature of the flow pattern during these two intervals. See Chapter 3 for more details on these additional constraints.

In Fig. 5.4 four representative examples of the northern hemisphere flow pattern are presented, imaged at 0200, 0400, 0600 and 0700 UT, which employ 2 min resolution data
Figure 5.3 SuperDARN line-of-sight velocity measurements from the radar beams indicated in Fig. 5.2 are shown for the interval 0130-0730 UT on 2 Dec 1999. The vertical dashed lines show the centre times of 6 pulsed flow features, which are discussed in detail in the text.
Figure 5.4 Streamlines and vectors of the ionospheric flow derived from the SuperDARN velocity measurements shown on geomagnetic grids, obtained from the 'Map-Potential' algorithm (see Chapter 3). Four maps are shown from the first 6 h interval studied here for the six northern hemisphere radars. Maps are shown at 0200, 0400, 0600, and 0700 UT for the northern hemisphere. The exact time interval of each map is indicated in the top left-hand corner, and at the bottom of each map the total transpolar voltage $V_{pc}$ (left-hand corner), and the direction and magnitude (in the Y-Z plane) of the lagged IMF (right-hand corner) are also indicated.
from the six radars indicated in Fig. 5.2. The icon in the bottom right hand corner of each plot indicates the direction and strength of the concurrent (lagged) IMF projected onto the y-z plane, emphasising again that although these flow data span 5 h of UT, the IMF conditions remained very similar. Correspondingly, although the details vary from plot to plot, the overall flow pattern also remained similar. It can be seen that the convection was consistently dominated by a large crescent-shaped ‘dusk’ flow cell, which spanned the local time interval roughly from noon (the details being inaccessible due to the lack of post-noon dayside data), via dusk into the post-midnight hours. A clear ‘dawn’ flow cell is present only in the map at 0400 UT, where it is confined essentially to the dayside MLT quadrant between dawn and noon. In general, the dawn sector flows are highly structured and variable, and appear to be essentially absent, for example, at 0600 UT. The sense of the dawn-dusk flow asymmetry is exactly that expected for Dungey-cycle flow driven in the presence of strong and consistent negative IMF By (Jørgensen et al., 1972; Cowley, 1981; Reiff and Burch, 1985; Ruohoniemi and Greenwald, 1996). In particular, the predominant sense of anti-clockwise vortical flow within the polar cap, giving faster antisunward flows at dusk than at dawn, is that expected to be produced by the east-west field tension effect on open field lines, which pulls newly-reconnected field lines within the dayside cusp eastward into the dusk sector. Despite the northward direction of the IMF, there is little evidence in these maps for the concurrent presence of high-latitude ‘lobe’ convection cells. However, as mentioned above, the lack of data coverage in the post-noon dayside quadrant makes this statement less than definitive.

As a further check on the nature and origin of the flow patterns, all available DMSP particle data and VIS auroral imagery during the interval have also been examined, in order to determine the nature of the concurrent particle precipitation patterns (though as noted above VIS images are available only until ~0300 UT). On the basis of the above interpretation, we would expect the central region of the convection patterns where the flow is directed antisunward but with an anti-clockwise vortical twist (in the northern hemisphere) to correspond to open field lines with cusp/mantle (on the dayside) or polar rain (on the nightside) precipitation, while the surrounding region at lower latitudes should correspond
to closed field lines with trapped BPS/CPS precipitation (e.g. Newell et al., 1991, 1996). Indeed, it is found that all the DMSP and VIS data are compatible with these expectations. An example is shown in Fig. 5.5, taken from early in the interval when VIS images were available, together with a simultaneous DMSP (F12 satellite) overpass. Fig. 5.5a shows the northern hemisphere SuperDARN flow vectors and Map Potential flow streamlines for the two minute scan 0150-0152 UT, in the same format as Fig. 5.4. This is superimposed on a simultaneous VIS image of the UV auroras, obtained over a 32.5 s integration centred on 0151:07 UT. The intensity of the UV emission is indicated in the bar on the right-hand side of the figure. The VIS data show a central region of almost no emission which agrees well in location with the region of antisunward and anticlockwise vortical flow in the convection map. This central region is taken to be the region of open magnetic flux. Surrounding this, a near-circular continuous ring of emission is observed, due to precipitating ~keV electrons, which generally closely coincides with the region of clockwise flow in the extended crescent-shaped ‘dusk’ convection cell. This region is taken to correspond, to a first approximation, to the region of trapped hot plasma on closed flux tubes.

Fig. 5.5a also shows the track of the DMSP F12 spacecraft as it passed over the polar regions during the interval 0145-0204 UT. The spacecraft position at the centre time of the VIS image (and also very nearly the centre time of the SuperDARN scan) is indicated by the red triangle. The track is colour-coded by the nature of the precipitation observed, i.e. CPS, BPS, cusp, and mantle. The data on which these classifications are based are shown in standard spectrogram format in Fig. 5.5b. It can be seen that the regions designated CPS/BPS lie within the region of UV auroral emission and sunward or clockwise vortical flow. The region of ‘mantle’ precipitation corresponds to the central region of weak emission and antisunward and anticlockwise flow in the post-noon sector, while the ‘cusp’ precipitation, taken to be indicative of newly-opened dayside field lines, extends across the poleward boundary of the UV emission near noon, in the region where the Map Potential streamlines turn poleward and eastward. Overall, these data (and those obtained in other VIS images and on other DMSP passes) provide significant support for our interpretation of the observed flows as asymmetrical Dungey-cycle convection patterns driven by dayside
Figure 5.5  (a) A map of the UV auroral intensity at 01:51:07 UT (the centre time of the 32.5 s integration interval of the UV image) projected onto a geomagnetic grid. Superposed on this image are SuperDARN 'Map-Potential' streamlines and flow vectors, and the orbital track of the DMSP F12 spacecraft from 0145-0204 UT, colour-coded to the different regions of particle precipitation (the red triangle indicates the footprint of the spacecraft at the time of the UV image). Also indicated on the map is the derived total transpolar voltage and the direction and magnitude (in the Y-Z plane) of the lagged IMF, as in Fig. 5.4. The superposed SuperDARN vectors correspond to the two minute interval which encompasses the centre time of the UV image.  (b) Standard precipitating particle spectrograms from the SSJ/4 instrument on board the DMSP F12 spacecraft for the overpass shown in (a). Electron (top panel) and ion (bottom panel) data are presented for 0145-0204 UT. Also indicated at the bottom of the figure is the magnetic latitude (MLAT) and magnetic local time (MLT) at corresponding universal times (UT).
and nightside reconnection. In particular, the cusp/mantle precipitation observed by DMSP on the pass displayed here in itself constitutes direct evidence of on-going dayside reconnection.

The data in Figs. 5.3-5 are thus indicative of the essentially continuous presence of flow driven by open flux tube production at the magnetopause and destruction in the tail during the interval. It is then important to emphasise that the approximately constant size of the flow patterns seen in Fig. 5.4 implies an approximate balance in the dayside and nightside reconnection rates over the interval as a whole. It can be seen, for example, that the flow reversal boundary and implied open-closed field line boundary near midnight stays within a few degrees of ~75° through the entire interval. Judging from the position of this boundary at various local times, the amount of open flux present in the system is typically \( \sim 4 \times 10^8 \) Wb (see later for more detailed estimates). The mean transpolar voltage for the entire interval was 35 kV, corresponding, of course, to a magnetic flux throughput in the flow system of \( \sim 35 \) kWb s\(^{-1}\). If this flow was associated with essentially unbalanced dayside reconnection and open flux production, the amount of open flux that would be created over the 6 h interval (across a small merging gap) would be \( \sim 8 \times 10^8 \) Wb, thus essentially tripling the amount of open flux present in the system. Clearly this does not happen. Similarly, if the flow was associated with essentially unbalanced nightside reconnection at this rate, the polar cap would contract to zero size in \( \sim 3 \) h. Clearly this also does not happen. (In addition, we would not expect the IMF \( B_y \)-associated flow asymmetry to persist in this case.) Rather, if a rough limit is set for the change in open flux over the interval of say \( \sim 1 \times 10^8 \) Wb, corresponding to a change in the overall boundary position of \( \sim 2^\circ \), the implied difference in the dayside and nightside reconnection rates averaged over the 6 h of the interval is \( \sim 5 \) kV, small compared with the overall voltages deduced from the flow of \( \sim 35 \) kV. The flow maps thus imply approximate balance between dayside and nightside reconnection rates, averaged over the whole interval, to within 10-15%. However, as will be shown below, this does not imply that detailed balance occurs throughout, as the pulsed nature of the nightside flows noted above already suggests.
5.1.3 Overview of substorm indicators

Given the implied existence of nightside reconnection at an appreciable average rate during this interval, it is of interest to enquire whether this process is expressed in terms of substorm expansions, as is characteristic of intervals of southward-directed IMF. Data relevant to this issue are summarised below. Fig. 5.6 shows the locations of the ground magnetic stations employed, indicated in the figure by the black circles on the same magnetic grids and at the same times as in Fig. 5.2. Also shown is the ionospheric footprint of LANL-97A, mapped from geostationary orbit using the T-89 model (Tsyganenko, 1989), indicated by the red coloured triangle, with the black solid line showing the footprint of a complete orbit.

Data have been inspected from all the magnetograms of the six northern hemisphere arrays detailed in Chapter 3. Data from selected stations will be presented, indicated in Fig. 5.6 by the coloured circles, and their identifier codes are also shown for reference. Data from those at lower latitudes and colour-coded red (i.e. PBQ, NAQ, and FAR) have been band-pass filtered (20-200 s) to provide information on substorm-related Pi2 signals. Those at latitudes ~70°-75° and colour coded blue (i.e. CON, IQA, and BJN) are distributed in longitude over the local time extent of the radar array to give an indication of the overall magnetic activity during each interval. Data will also be shown from a number of sub-arrays, colour-coded yellow, which span individual features at much higher spatial resolution, thus enabling a more detailed analysis.

The top three panels of Fig. 5.7 present $H$ component magnetograms from the azimuthal magnetometer array (colour-coded blue in Fig. 5.6), which are examined for the presence of magnetic signatures indicative of the formation of substorm electrojets. These stations are at a higher latitude than those at which substorm expansion onsets usually occur during or directly after intervals of southward IMF (~65°), but they are relevant in the present context in view of the contracted nature of the flow patterns displayed in Figs. 5.4 and 5.5. It has also been confirmed that they are representative of all the data from all the networks
Figure 5.6 Ground-based magnetometer locations and the LANL spacecraft footprint at the start and end times of the 02 Dec 1999 interval on the same grid as in Fig. 5.2. Red dots indicate stations whose data has been band-pass filtered to provide information on Pi2 signals. Blue dots indicate three stations which span the local time extent of the radar fields-of-view. Yellow dots indicate stations which span individual events which are studied in detail. The black oval represents the ionospheric footprint of geostationary orbit.
Figure 5.7 The upper three panels show H component magnetic field measurements from the blue colour-coded array in Fig. 5.6, for 0130-0730 UT on 2 Dec 1999. Panels 4-6 show filtered (20-200 s) H-component magnetic field measurements from the low-latitude magnetometer array (red dots in Fig. 5.6) for the same interval. The bottom panel shows geostationary electron fluxes in two energy channels (50-75 keV and 75-105 keV) from the SOPA instrument on the LANL-97A spacecraft. The vertical dashed lines correspond to those in Fig. 5.3.
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surveyed in this study. These data show that the geomagnetic field was ‘quiet’ during the whole interval with no indications of impulsive substorm activity. Field variations were continuously present on time scales of several tens of minutes, but the amplitudes were typically only a few tens of nT. There is some evidence of a relationship between these variations and those in the flow, marked by the vertical dashed lines as in Fig. 5.3, and this will be discussed later.

The lack of impulsive substorm-like activity is emphasised in the next three panels of Fig. 5.7, which show representative magnetic field data from lower-latitude stations (colour-coded red in Fig. 5.6) which have been filtered between 20-200 s, corresponding to the Pi2 band. None of these data (including those from stations not shown here) indicate any impulsive substorm-like Pi2 features, though the data from NAQ does indicate some continuous activity of amplitude ~1 nT during the first ~2 h of the interval. However, there does not appear to be any detailed correspondence between this low-level activity and the times of the flow features discussed above.

Finally, data from three operating LANL spacecraft, 1994-084, 1989-046, and LANL-97A have been examined. During most of the interval, LANL-97A was located in the dawn sector (see Fig. 5.6), in the most appropriate location of the three satellites for monitoring electron injections. Two channels of energetic electron data are presented in the bottom panel of Fig. 5.7, being representative of the entire data set. Small periodic flux variations are evident over the interval, but no injection signatures are present, or any obvious relationship to the flow features, as is indeed the case in the data from all the LANL spacecraft. Thus if particle injections from the tail did occur, they did not reach geostationary orbit. Overall, therefore, there are no indications of substorm bays, Pi2s, or geostationary orbit particle injections having been observed during the interval. The tail reconnection which occurred was therefore not manifest as classic near-Earth substorm expansions. Nevertheless impulsive activity was indeed observed in the nightside flow, as noted above, and in the next section we turn to examine its behaviour in more detail.
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5.1.4 Nightside flow bursts

The variability of the nightside flow, whose presence is already indicated in the data presented in Figs. 5.3 and 5.4, is now examined more closely. In Fig. 5.8 parameters which have been extracted from the Map Potential plots are shown, which provide measurements of the variability of the flow. The top panel shows the total transpolar voltage in the flow maps, representing a measure of the total flux transport in the flow system. The level of confidence in this parameter in general depends on the coverage of the polar ionosphere by the radar data. Examination shows that during this interval the data generally do span the extrema in the voltage values (see e.g. Fig. 5.4), so that we may have reasonable confidence overall. It can be seen that the voltage values typically lie between ~25 and ~50 kV, and exhibit intervals of relatively steady values close to the mean of 35 kV, interspersed at roughly 1 h intervals with enhancements lasting ~10-15 min during which the voltage increases up to peaks of ~40-50 kV.

Inspection of the flow maps shows that these enhancements are manifest as localised bursts of fast flows, generally located in the westward ‘dusk’ cell flow spanning the midnight sector. The second panel of Fig. 5.8 then shows a complementary measure of the flow variations, namely the peak nightside flow speed occurring in each 2 min Map Potential plot specifically in these westward ‘return’ flows. In order to provide a representative value, the vector velocities have been averaged in bins which are 220 km square, corresponding to 2° latitude and typically ~7° longitude, representing four ‘pixels’ of the Map Potential algorithm. Again, the bursty nature of the flow is evident. Typical values of ~500-800 m s$^{-1}$ are interspersed with ~10-15 min bursts reaching up to ~1500 m s$^{-1}$. The averaged value of the peak flow speed over the interval, 891 m s$^{-1}$, is indicated by the horizontal dotted line in this panel, emphasising the peaks in the flow. The most prominent and long-lived of these peaks are marked by the vertical dashed lines, these being the same lines as those shown previously in Figs. 5.3 and 5.7. Comparison with the data in the upper panel of Fig. 5.8 shows that most of the peaks in the speed also correspond to a peak in the transpolar
Figure 5.8 Flow measurement time-series obtained from the SuperDARN radar observations and the 'Map-Potential' algorithm. The top panel shows the total transpolar voltage, $V_{PC}$. The second panel shows the peak nightside ionospheric flow speed (the horizontal dotted line is the average over the interval), and the third, the north-south (dotted line) and westward (solid line) components of the peak flow. The bottom two panels show the location of this peak flow in magnetic latitude (fourth panel) and MLT (bottom panel). The vertical dashed lines indicate six peaks in the flow speed, corresponding to those in Figs. 5.3 and 5.7.
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voltage. This indicates that an overall enhancement in the flux transport took place in association with the flow bursts, and not just a reconfiguration in the flow pattern.

The third panel of Fig. 5.8 shows the vector components of the flow associated with the peak speed shown in the second panel. The solid line shows the westward flow component (perforce positive since the peak flow speed displayed corresponds specifically to the westward flow of the ‘dusk’ return cell), while the dashed line shows the north-south flow (positive equatorward). These data show that, with the exception of the burst peaking at 0716 UT, the peak flows all occur in the westward component. Concurrent changes in the north-south component are also observed, however, with enhancements in the equatorward component often occurring in the vicinity of the peak in the westward flow. The lower two panels of the figure also show the magnetic latitude and MLT of the location of the peak flow speed. It can be seen that the latitude of the peak flow is generally located in the range 73°-75°, and shows little trend during the interval, consistent with our previous discussion concerning the lack of overall change in the size of the flow system. Similarly the local time of the peak flow speed is scattered ~2-3 h on either side of midnight, and also shows no overall preference or trend.

5.1.4.1 Flow burst geometry

Having investigated the overall nature of the nightside flow data, we now examine in more detail the nature of the flow variations which occur in two of the flow bursts, those centred near (and indicated by the vertical lines at) 0300 and 0518 UT. Fig. 5.9a shows eight selected 2 min flow maps which span the first of these intervals, between 0236 and 0320 UT. The black triangles in these plots show the positions of key ground magnetometer sites whose data will be examined below. The first map, for the 2 min interval starting at 0236 UT, is illustrative of the nature of the flow over the previous ~20 min interval. It shows a well-formed IMF $B_y$-asymmetric flow pattern of modest intensity, in accordance with the overview presented above, with a well-developed crescent-shaped ‘dusk’ flow cell stretching from noon via dusk to the post-midnight hours, together with a weaker rounder
Figure 5.9a Flow maps illustrating the flow burst interval 0236-0320 UT, shown in the same format as Fig. 5.4. Four selected maps are shown here from the first half of the interval. The exact time of each 2 min map is indicated in the top left-hand corner. Also indicated on the maps by the black triangles are the locations of the magnetometer stations colour coded yellow in Fig. 5.6.
Figure 5.9a (cont.) Four selected maps from the second half of the 0236-0320 UT burst interval.
‘dawn’ flow cell which is centred in the pre-noon sector. The transpolar voltage is estimated to have been 35 kV. Over the next ~15 min the dusk cell flow then grew in magnitude, with fast equatorward flows near midnight, and fast westward ‘return’ flows in the pre-midnight sector, which eventually extended to the edge of the radar field-of-view at ~19 MLT. The transpolar voltage reached 44 kV at 0252 UT, and remained at around that value for the next ~20 min. Rapid equatorward and westward flows were also observed in the dawn sector after this time, which, bearing in mind the asymmetric nature of the flow pattern, could also have been connected with the enhancements observed nearer to midnight. The flow magnitude fell rapidly after 0312 UT, however, such that the transpolar voltage reduced to values of ~35 kV by 0320 UT similar to that occurring before the burst.

Fig. 5.9b shows in the same format the development of a second flow burst during the interval from 0502 to 0530 UT. The first map, starting at 0502 UT, shows a weak flow pattern with a transpolar voltage of 31 kV which is dominated by clockwise vortical ‘dusk’ cell convection. The ‘return’ flows in the pre-midnight sector were relatively strong, however, as had been the case for the previous ~20 min. These flows persisted until ~0506 UT, when an enhancement began in the pre-midnight sector, which developed over the next ~15 min into a predominately azimuthal flow feature spanning some 6 h of MLT about the midnight meridian (within the fields-of-view of the radars), and containing flows which peaked at ~1500 m s⁻¹. Peak estimated transpolar voltages of ~40 kV occurred at ~0520 UT, the flows then subsequently declining to reach transpolar voltages of ~30 kV once more after ~0530 UT.

Overall, the geometry of these two flow burst events are seen to be similar to each other, both involving a strong enhancement in the nightside westward dusk cell ‘return’ flow. However, in the second case the region of rapid equatorward flow out of the polar cap appears to have shifted from near midnight into the post-midnight sector, such that the region of enhanced westward flow also moved eastward to span the midnight sector. Fig. 5.9c shows a gallery of flow maps taken from the centres of each of the remaining bursts that occurred during the interval, at the times indicated by the vertical dashed lines in
Figure 5.9b (cont.) Four selected maps from the second half of the 0502-0530 UT burst interval.
Figure 5.9c  Maps corresponding to the centre times of each of the other four bursts indicated on Fig. 5.8 by the vertical dashed lines.
Fig. 5.8. Within the limits of the radar data coverage, each of them displays an enhancement in the westward dusk cell ‘return’ flows in the pre-midnight-to-midnight sector, with enhanced equatorward flows out of the polar cap in the midnight-to-post-midnight sector. The burst centred at 0144 UT also shows the presence of rapid equatorward flows in the dawn sector, with westward flows extending into the pre-midnight sector, which may be a related phenomenon.

5.1.4.2 Bursts as nightside reconnection events

The geometry of the flow surges revealed by the above analysis suggests that they are formed by bursts of enhanced reconnection in the geomagnetic tail. If so, we might expect them to be associated with overall poleward contractions in the open-closed field line boundary and in the flow pattern. It is evident from the flow maps shown in Fig. 5.9 that only in certain cases do the flow data consistently define a sharp flow reversal boundary whose motion can be reasonably clearly followed over the duration of the burst, and then only over a limited local time interval in the pre-midnight sector. It is primarily for this reason that the following analysis is made of just the first of the two bursts discussed above. In Fig. 5.10 data are shown for the interval 0230 to 0330 UT. The top panel shows the transpolar voltage obtained from the Map Potential plots, showing the enhancement in the overall flux transport during the burst, while the dashed vertical lines delimit the central ~30 min interval of enhanced flows. The lower panel shows the latitude of the peak potential in the Map Potential plots in the pre-midnight sector, corresponding to the east-west flow reversal, specifically for 21 MLT (as dictated by the coverage of radar data). These values are quantised in units of $1^\circ$ by the Map Potential algorithm. Again, the central ~30 mins of enhanced flows are delimited by the vertical dashed lines. The 2-3 points immediately after the burst, which suggest a sudden drop in the latitude of the boundary appear to be associated with an additional, smaller-scale flow feature near to midnight and are therefore unlikely to be representative of the location of the boundary elsewhere. Despite this, and the evident scatter and the quantisation, these data do suggest the occurrence of a small poleward contraction of the boundary across the event, by $\sim 1^\circ - 2^\circ$. 

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Figure 5.10 The total transpolar voltage $V_{PC}$, derived from SuperDARN radar data using the 'Map-Potential' algorithm (top panel) and an estimate of the latitude of the nightside flow reversal boundary ($\Lambda_B$) obtained from the minimum in the electrostatic potential (determined at 21 MLT) (bottom panel). Data is shown from 0236-0336 UT for the 02 Dec interval. The vertical dashed lines delimit the ~30 min duration of each burst.
from $\sim 76^\circ$ to $\sim 78^\circ$. Extrapolated around the boundary of the polar cap, such a displacement implies a net closure of open flux of $\sim 1 \times 10^8$ Wb due to enhanced tail reconnection exceeding the concurrent dayside reconnection rate during the burst interval. The implied difference in rates is by several tens of kV averaged over the duration of the burst. A more detailed analysis is presented below, which attempts to quantify the dayside and nightside reconnection rates during the burst interval within the limitations of the available data.

5.1.4.3 Burst magnetic signatures

Although the above data suggest that the observed flow bursts are due to intervals of enhanced reconnection in the tail, it has already been demonstrated above that they are not associated with classic substorm features. However, small amplitude fluctuations do occur in the nightside magnetometer data during the interval, and we now investigate the relationship of these variations with those in the flow data. Fig. 5.11 presents magnetometer data for each of the two bursts, from the high-spatial resolution array (yellow dots) shown in Fig. 5.6. This array is also indicated by the black triangles on each of the flow maps in Fig. 5.9. For each burst the perturbation field is shown superposed with the flow data from the 220 km square bin corresponding to the location of the magnetometer (such that the location of the bin corotates with the station). If the horizontal perturbations are due to overhead Hall currents, then they should correlate with the flow variations according to $\Delta H \propto \Sigma_H V_W$ and $\Delta D \propto \Sigma_H V_N$, where $H$ and $D$ are the northward and eastward components of the magnetic perturbation respectively (as before), $V_W$ and $V_N$ are the westward and northward components of the flow, and $\Sigma_H$ is the height-integrated ionospheric Hall conductivity. Such simple relationships will not always hold, particularly in high spatially structured circumstances, due to the integrating nature of ground-based magnetic observations. However, they should be approximately valid here, where the spatial scale for variations in the flow is several 100 km as can be seen in Fig. 5.9. It was noted above that low-amplitude Pi2-band (5-50 mHz) activity was present during the intervals. The filtered data are therefore also shown from the same stations, to ascertain whether there is any localised activity which might be related to the bursts.
Figure 5.11a-b The $H$, $D$ and $Z$ components of the ground magnetic field measured by the stations colour-coded yellow in Fig. 5.6, and indicated in Fig. 5.9 by the black triangles. (a) The perturbation field (solid lines) for the interval 0230-0330 UT on 2 Dec 1999, superposed with the east-west (in (i)) and north-south (in (ii)) SuperDARN flow components (dashed lines) corresponding to the locations of the magnetometers. (b) The same magnetic data, band-pass filtered (20-200 s) to highlight Pi2-band activity. The scales to the left of each plot indicate the range between the baselines (horizontal dotted lines) and the vertical dashed lines are as in Fig. 5.10.
Figure 5.11c-d: As Fig. 5.11a-b, but for the interval 0400-0540 UT.
Fig. 5.11a presents the magnetic and flow data for the first burst. In this figure, and in Figs. 5.11b-d, the vertical dashed lines correspond to those in Fig 5.10, delimiting the ∼30 min burst duration. Panel (i) contains the $H$-component magnetic field data (solid line), and the overhead westward component of the flow (dashed line), as discussed above. Although the two curves do not agree everywhere, certain features are present in both data sets. For example, an enhancement in the flow at the location of BLC is accompanied by an increase in the local $H$-component. In panel (ii), which contains the $D$-component magnetic field data and the similarly-corresponding northward component of the flow (dashed line), there is also some correlation between the two. For example, the enhanced equatorward flows seen at the location of IQA are accompanied by a coincident negative bay in the field.

If we take values of ∼1000 m s$^{-1}$ for the flow speed, and magnetic perturbations of ∼50 nT, then the implied value of $\Sigma_H$ is just a few mho. Although as indicated above it can in general be dangerous to relate local fields and flow in this way, we can confirm that only low-amplitude magnetic effects were observed over the whole array of stations examined here. This, together with the general lack of consistent correspondence between the field perturbations and the flow, suggest that the auroral precipitation during these events within the region of enhanced flow was very low, certainly by comparison with substorm intervals.

Finally, panel (iii) contains the $Z$-component magnetic field data which shows similar fluctuations to the other two components and a large negative deflection at ∼0310 UT. This feature can also be identified in the $H$ and $D$ components, but has no clear signature in the flow data.

In Fig. 5.11b the same magnetometer data is shown band-pass filtered between 20-200 s as discussed above. Station RAN measured the largest amplitude activity in the $H$ and $D$ components, but this does not appear to be related to the time of the burst. At CHX, IQA, and BLC, however, there is some evidence of enhanced activity during the burst, although this is of a more continuous nature, unlike the impulsive Pi2-signatures typical of substorms.
Figs. 5.11c and 5.11d present data in the same format for the second burst. The magnetometer and flow data in Fig. 5.11c show similar trends to those for the first burst, although there now appears to be a rather clearer correlation between the two data sets in this case. This is particularly evident in the $H$-component magnetometer and east-west flow data. Again, the amplitudes of the correlated perturbations are such that the values of $\Sigma_H$ implied by these data are no more than a few mho, suggesting that, as in the previous example, no strong conductivity changes are present and hence no strong precipitation.

Figure 5.11d shows the filtered (20-200 s) magnetometer data for this burst. The general picture is much the same as for the first burst, with some small amplitude activity observed at certain stations. In particular, there appears to be a well defined 'onset' of low-amplitude activity observed at CHX and BLC associated with the central time of the burst, at \( \sim0518 \) UT.

### 5.1.5 Interval 1 summary

During this interval, in which an IMF clock angle of \(-60^\circ\) was maintained for \( \sim6\) h, dayside reconnection continued to drive Dungey-cycle flow in the magnetosphere-ionosphere system. It is found that, over the entire interval, the size of the convection pattern remained relatively constant, implying that tail reconnection was also ongoing, at an average rate approximately equal to that on the dayside. However, the usual substorm cycle did not occur, evidenced by the lack of magnetic bay signatures at high latitudes, Pi2 signals, and geostationary orbit energetic particle injections. Instead, \( \sim1000\) m s\(^{-1}\) bursts of flow were observed in the nightside ionosphere lasting a few tens of minutes and recurring every hour or so, accompanied by weak magnetic signatures and low amplitude Pi2-band (5-50 mHz) activity. One burst studied in detail, for which there was a well defined flow reversal boundary in the flow data, appeared to coincide with a \( \sim1^\circ-2^\circ\) contraction of the boundary. These data thus indicate that the bursts are associated with intervals of enhanced tail reconnection, during which the tail reconnection rate temporarily exceeds the dayside reconnection rate.
5.2 Observations Overview: Interval 2 (2100 UT 14 December - 0300 UT 15 December 1999)

In this section the ground and space observations made during the second 6-hour interval (14/15 Dec 1999) are discussed.

5.2.1 Upstream interplanetary conditions

During this second interval, the ACE spacecraft was located at GSM coordinates $(X,Y,Z) = (226,36,-15) \text{R}_E$. Fig. 5.12 presents the ACE interplanetary data in the same format as Fig. 5.1, lagged by 68 min, for the 18 hour interval from 1500 UT on 14 December to 0900 UT on 15 December 1999. The steady nature of the solar wind during the main region of interest is evidenced in the proton number density ($n_p$) and speed ($v_p$) data. The density remained relatively constant at $\sim 5 \text{ cm}^{-3}$ and the velocity between 370-420 km s$^{-1}$. The IMF was also steady throughout the main interval. $B_x$ was near zero or negative, $B_y$ was large and negative, and $B_z$ was predominantly positive (and had been for the previous 6 h). This translates to a total field strength of $\sim 8 \pm 2 \text{ nT}$, and a clock angle with a mean value of $-51^\circ$ and a standard deviation of $15^\circ$. However, it may be noted that a small change in the field occurred near the middle of the interval ($\sim 0030$ UT), such that the field magnitude and clock angle were modestly increased in the later period compared with the earlier.

5.2.2 SuperDARN flow data overview

Fig. 5.13 shows the fields-of-view of the six northern hemisphere SuperDARN radars at the start and end times of the second interval, i.e. 2100 and 0300 UT, in the same format as Fig. 5.2. In this case, the line-of-sight data (shown in Fig. 5.14) are from the Goose Bay, Iceland West, Iceland East and Finland radars. In common with the previous interval, continuous flow was observed over the entire 6 hours, with speeds of $\sim 500-1000$ m s$^{-1}$. These flows are predominantly directed towards the radar at Goose Bay (beam 13) and Iceland East (beam 12) indicative of westward ‘return’ flows in an azimuthally extended
Figure 5.12  Upstream interplanetary observations as in Fig. 5.1 for 1500 UT on 14 Dec to 0900 UT on 15 Dec 1999, lagged by 68 min to account for the propagation delay to the ionosphere. The top two panels show solar wind density and velocity data, the middle three panels show IMF data in GSM co-ordinates, and the bottom two panels show the field magnitude and clock angle.
Figure 5.13 Fields-of-view of the six northern hemisphere SuperDARN radars at 2100 (top) and 0300 UT (bottom), the start and end times of the 14/15 Dec 1999 interval. These are plotted on a geomagnetic grid from the pole to 60°, with 12 MLT at the top and dusk to the left. Fields-of-view coloured blue are those of the four radars for which detailed line-of-sight measurements will be discussed, using the beams indicated in red.
Figure 5.14 SuperDARN line-of-sight velocity measurements from the radar beams indicated in Fig. 5.13 are shown for the interval 2100-0300 UT on 14/15 Dec 1999. The format is the same as Fig. 5.3.
dusk convection cell, and away from the radar at Iceland West (beam 3) indicative of sunward ‘return’ flow in the same cell. At Finland (beam 4) for the early part of the interval and Iceland West (beam 8) for the later part, the flows are both towards the radar in the more poleward ranges and away from the radar in the near ranges, indicative of equatorward flow out of the polar cap with a flow reversal in the auroral zone. Again, there is also evidence of strong variability in the flow, which is particularly marked, for example, in the Iceland West data. However, this variability is of a less regular nature than that observed during the previous interval (see Fig. 5.3). The vertical dashed lines indicate episodes of high flow variability which will be discussed further below. To a first approximation, however, this is a similar interval to that discussed above, with dynamic and often high speed flows, driven during an interval of northward and $B_y$-dominated IMF.

Inspection of data relevant to the identification of substorms (not shown here) also suggests that this is a similar interval to that described above. The $H$ component magnetometer data again shows only small field variations of a few tens of nT amplitude, indicative of a ‘quiet’ geomagnetic field, similar to that on 2 December shown in Fig. 5.7. The lack of substorm activity is emphasised in the filtered data, none of which indicates any impulsive substorm-like Pi2 features. Representative data from the LANL-97A SOPA instrument (located in the dawn sector) also indicate no injection signatures or indeed any significant variations in the particle fluxes. Overall, therefore, this interval appears to be as devoid of substorm activity as the first. Nevertheless, as mentioned above, impulsive nightside activity was again observed in the flow, which is now examined.

5.2.3 Nightside flow bursts

Fig. 5.15 presents flow parameters extracted from the Map Potential plots as before. The voltage values, again shown in the top panel, typically lie between ~20 and ~40 kV. The average over the interval was 29 kV. This is somewhat less than the average during the first interval, possibly owing to the slightly reduced IMF magnitude and clock angle. Nevertheless, the values do exhibit a similar variability. The plot of the peak nightside flow
Figure 5.15 Flow measurement time-series, obtained from the SuperDARN radar observations and 'Map-Potential' algorithm for 2100 0300 UT on 14/15 Dec 1999. The format is the same as Fig. 5.8.
speed, however, appears to be divided into two distinct parts. The first half of the interval (up to ~0030 UT) appears relatively quiet, with typical values of the peak flow around ~600-800 m s\(^{-1}\) (close to the averaged value of the flow speed over the full 6 h of 732 m s\(^{-1}\)). Only one apparent 'burst' occurred, at ~2240 UT. Then, after ~0030 UT, the peak flows more resemble those during the first interval, with regular burst-like features evident in the data, reaching speeds up to ~1200 m s\(^{-1}\). This change in flow characteristic could be associated with the modest concurrent change in IMF conditions which was noted above.

Those bursts which can be distinguished from these data (and from a close inspection of the flow maps) have been marked by the vertical dashed lines, corresponding to those in Fig. 5.14. Comparison with the data in the upper panel of Fig. 5.15 shows that the peaks which have been identified in the flow speed also generally correspond to peaks in the transpolar voltage. This is consistent with our conclusion about the bursts during the first interval, in that an overall enhancement in the flux transport took place in association with the flow bursts. However, it is also evident that substantial enhancements in the transpolar voltage occurred at times when no flow speed excitation is apparent in the nightside data. This generally occurred early in the interval when the radar coverage included a significant portion of the dayside ionosphere, and, as can be inferred from the flow maps, the voltage enhancements were then significantly influenced by the dayside driven component of the flow.

The vector components of the peak flow also show a similar trend to the corresponding data from the first interval. The bursts tend to peak in the westward direction (indicated by the solid line), with relatively little enhancement in the north-south component (dashed line). The latitude of the peak flow is generally located in the range 69°-73° (a few degrees lower than observed for the 2 December interval) and does not show significant trends over the interval. This is again consistent with our previous discussion concerning the lack of overall change in the size of the flow pattern. There is some scatter in the local time of the peak flow speed, although around the times of the bursts, specifically in the second half of the interval, the flows did tend to peak consistently within 1-2 h of midnight.
5.2.3.1 Flow burst geometry

As indicated above, the variability of the flows observed here differs somewhat from that observed during the first interval, particularly in the initial period. Although the background flow pattern is similar, being driven under the influence of large negative IMF-B_y, the tail does not seem to respond with quite the same impulsive regularity as before. In Fig. 5.16a four representative examples of the northern hemisphere flow pattern are presented, from 2130 UT on 14 December to 0030 UT on 15 December, representative of the 'quiet' half of the interval, as described above. Although the details vary from plot to plot, the overall flow patterns remain similar to each other, and to that observed during the previous interval (see Fig. 5.4). Owing to the earlier UT of this interval, however, there is much better coverage of data in the post-noon sector, which shows the existence of dayside anti-sunward flows in the throat of the convection cells, indicative of dayside reconnection. There is also some evidence early on in the interval for the concurrent presence of high-latitude 'lobe' convection cells. Later in the interval, in the map at 0030 UT for example, a 'dawn' flow cell is also apparent, confined essentially to the same dayside MLT quadrant between dawn and noon as in the previous interval. In general, however, the lack of data in the dawn hours makes it difficult to draw conclusions about the nature of the flows in that sector. The extended nature of the dusk flow cell does nevertheless imply the existence of the expected dawn-dusk flow asymmetry.

The asymmetry is corroborated by the southern hemisphere data (not shown). These data again show much more restricted coverage than in the north, but are consistent with the opposite asymmetry in the flow. Examination of all available DMSP particle data for the interval provides similar corroboration of the open nature of the polar cap. A number of southern hemisphere overpasses by the F13 and F14 spacecraft, in particular, provided good evidence of a band of CPS/BPS precipitation at ~75° (observed at 21, 05, and 09 MLT), with lower energy polar cap precipitation polewards of this.
Figure 5.16a SuperDARN flow maps in a similar format to those shown in Fig. 5.4. Four maps are shown here from the 'quiet' half of the 6 h interval, on the half hour for 2130-0030 UT. The exact time of each 2 min map is indicated in the top left-hand corner.
Chapter 5  Ionospheric flow during intervals of northward but $B_y$-dominated IMF

Although this interval is therefore not identical to the first, it is important to point out that some bursts are still observed, particularly in the second half. The centre times of five enhancements in the flow are indicated in Fig. 5.15 by the vertical dashed lines at 2240, 0052, 0130, 0210, and 0240 UT. As mentioned above, the first half of the interval sees only one distinctive burst (the start of which can be seen in the 2230 UT map of Fig. 5.16a). In this instance, the burst takes the form of enhanced sunward return flows in the dusk convection cell. During the second half of the interval, when the flow variability was enhanced, the bursts begin to take the form of azimuthal flows in the midnight sector, more like the bursts observed during the first interval. However, they are noticeably less discrete than before, with the flows varying more randomly in magnitude.

The burst centred at ~0210 UT is perhaps the best example, and exhibits similar characteristics to the bursts shown in Fig. 5.9. Fig. 5.16b therefore shows four flow maps which span this burst between 0154 and 0218 UT. The black triangles again show the positions of key ground magnetometer sites whose data will be examined below. The first map, starting at 0154 UT, is illustrative of the nature of the flow over the ~20 min period since the end of the previous burst. It shows an IMF $B_y$-asymmetric flow pattern, with evidence of some enhancement of the westward flow near midnight, and a relatively low transpolar voltage of 24 kV. Over the next ~20 min the westward flow in the midnight sector grew in magnitude, peaking at 0210 UT, with a corresponding peak in transpolar voltage of 38 kV. In the third map, showing this central time of the burst, the flow enhancement consists primarily of westward flows spanning magnetic midnight, similar to a number of the bursts observed during the first interval. Over the following ~10 min the flows subsided, with the transpolar voltage falling to 24 kV by 0218 UT.

The main conclusion to be drawn is that, as in the first interval, continuous quasi-steady Dungey-cycle flow was driven during this 6 h interval of steady interplanetary conditions. This implies again that there must be a consistent nightside reconnection-driven element to the flow which is balancing the observed dayside driving, but which is not manifest as typical substorm phenomena.
Figure 5.16b SuperDARN flow maps in a similar format to those shown in Fig. 5.4. Four maps are shown from the 0210 UT burst interval spanning 0154-0218 UT. Also indicated on the maps by the black triangles are the locations of several magnetometer stations, data from which are shown in Fig. 5.17.
5.2.3.2 Burst magnetic signatures

Fig. 5.17 presents magnetometer data for the burst from the array of magnetometers shown by the triangles in Fig. 5.16b. Fig. 5.17a presents unfiltered magnetic data along with the corresponding flow components, in the same format as in Fig. 5.11. Panel (i) contains the $H$-component magnetic field data (solid line), and the overhead westward component of the flow (dashed line). As found for the bursts during the first interval, there is no consistent correlation between the two datasets. Certain features are present in both, for example, an enhancement in the flow at the location of SKT is accompanied by an increase in the local $H$-component. In the $D$-component and the corresponding northward flow (dashed line), shown in panel (ii), there is a similar correlation. Again, however, values of $\sim 1000$ m s$^{-1}$ for the flow speed, and magnetic perturbations of at most $\sim 50$ nT (at these or any of the stations examined here), imply a Hall conductance of a few mho or less, indicative of a low level of auroral precipitation during these events within the region of enhanced flow.

The same magnetometer data are shown in Fig. 5.17b, band-pass filtered between 20-200 s. Station RAN measured the largest amplitude activity in the $H$ and $D$ components, but this does not appear to be related to the time of the burst. Indeed, none of the stations show discernable variability in the Pi2 band over the hour of the plot.

5.2.4 Interval 2 summary

The second of the two $\sim 6$ h intervals occurred under similar interplanetary conditions to the first. The IMF clock angle remained relatively constant at $\sim -50^\circ$, somewhat smaller than for the first interval, and the field intensity remained between 6 and 8 nT, also somewhat smaller than before. Dayside reconnection again continued to drive Dungey-cycle flow, although it was observed to be weaker than during the first interval, possibly due to the reduced clock angle and field strength. As before, it was found that the size of the convection pattern remained relatively constant over the entire interval, thus implying that tail reconnection was again ongoing at an average rate approximately equal to that at the
Figure 5.17  The $H$, $D$ and $Z$ components of the ground magnetic field for the interval 0140-0240 UT on 14/15 Dec 1999, measured by the stations indicated in Fig. 5.16b by the black triangles. Also shown are the east-west (in (i)) and north-south (in (ii)) SuperDARN flow components corresponding to the locations of the magnetometers. In (b) the magnetic field data have been band-pass filtered (20-200 s) to highlight Pi2-band activity. The scales to the left of each plot indicate the range between the baselines (horizontal dotted lines) and the vertical dashed lines delimit the ~30 mins burst duration.
dayside. The lack of substorm phenomena was again evidenced in the magnetic and geostationary orbit energetic particle data, while detailed investigation of the flow data revealed that similar nightside flow bursts occurred. However, only one clear burst was observed during the first half of the interval, with more frequent ‘bursty’ activity occurring during the second half. This change in the nature of the flow coincided with a small change in the IMF conditions, in which the field magnitude was slightly increased and the clock angle slightly reduced. Nevertheless, the basic nature of the bursts appears to be similar to those observed during the first interval.

5.3 Reconnection rates during burst intervals

The analysis of the principal nightside flow bursts described above shows that the transpolar voltage is enhanced during the bursts, and also suggests (somewhat less strongly) that a modest poleward displacement takes place in the nightside open-closed field line boundary (see Fig. 5.10). These features indicate that the bursts are associated with enhancements in the nightside reconnection rate. These data are analysed further below, in an attempt to quantify the reconnection rates within the limitations of the information available. The theoretical framework of our discussion is the Cowley and Lockwood (1992) paradigm of reconnection-associated flow excitation, leading to the reconnection-rate formulas derived previously in Chapter 4.

The physical situation which applies here is shown in Fig. 5.18 (where for simplicity the By-associated asymmetry is not represented), in which dayside and nightside reconnection are assumed to be both continuously present, but that the rate of flux closure on the nightside exceeds that on the dayside, such that overall the polar cap contracts. In this diagram the segments of the open-closed field line boundary mapping to the reconnection sites (i.e. the ‘merging gaps’) are shown by the dot-dashed lines, while the adiabatic segments of the boundary (which are not so connected and which thus move with the flow) are shown by the heavy solid lines. The lighter arrowed lines show the plasma streamlines. The action of the
Figure 5.18 Schematic of the flow situation appropriate to the burst intervals examined here, in which dayside and nightside reconnection are both continuously present, but with the rate of flux closure on the nightside exceeding the rate of open flux creation at the dayside, such that overall the polar cap contracts. The segments of the open-closed field line boundary mapping to the reconnection sites (i.e. the 'merging gaps') are shown by the dot-dashed lines, while the adiabatic segments of the boundary (which are not so connected and which thus move with the flow) are shown by the heavy solid lines. The lighter arrowed lines again show the plasma streamlines, and the large arrows show the implied boundary motion.
flow is to transport closed flux from the merging gap region of closure sunward to other local times, such as (in effect) to distribute the newly closed flux around the boundary. In the Cowley-Lockwood paradigm the flux is distributed uniformly round the boundary, such that it contracts with shape unchanged. A key feature of the diagram is that the foci of the plasma flow cells under these circumstances will be located near the ends of the nightside merging gap (see also e.g. Siscoe and Huang (1985)). At these points the plasma flow across the boundary will reverse from being directed equatorward in the sector of the merging gap, to being poleward in the contracting adiabatic sector on either side. It is therefore expected in this case that the total transpolar voltage (as estimated from the SuperDARN radar data) will correspond to the ionospheric voltage across the nightside merging gap. By the same argument, when dayside reconnection dominates, the transpolar voltage will correspond instead to the ionospheric voltage across the dayside merging gap. These conclusions would not follow if, for example, significant voltages are also present associated with 'lobe' convection cells. However, as indicated above, no evidence has been found for a substantial contribution from such flows cells in the data examined here.

Under these conditions it has been shown in Chapter 4 that the nightside and dayside reconnection rates averaged over some interval \( \tau \), \( \langle \Phi_n \rangle \) and \( \langle \Phi_d \rangle \), respectively, can be estimated from

\[
\langle \Phi_n \rangle = -\langle V_{PC} \rangle + f_{mg} \frac{B_i \Delta A}{\tau} \quad \text{and} \quad \langle \Phi_d \rangle = \langle V_{PC} \rangle + \left(1 - f_{mg}\right) \frac{B_i \Delta A}{\tau} .
\] 

(5.1a,b)

Here the reconnection rates are represented in terms of the rates of change of the amount of open flux \( \Phi \), such that by definition \( \langle \Phi_n \rangle \) is negative while \( \langle \Phi_d \rangle \) is positive. In these equations \( \langle V_{PC} \rangle \) is the averaged polar cap voltage as obtained from the SuperDARN data (assumed equal to the voltage across the nightside merging gap as indicated above), \( B_i \) is the polar magnetic field strength (taken to be constant for simplicity and equal to 60,000 nT), \( \Delta A \) is the change in the area of open flux over the interval (negative for a contraction), and \( f_{mg} \) is the fraction of that area associated with the motion of the nightside merging gap. If the contraction is uniform, as assumed in the Cowley-Lockwood paradigm, then \( f_{mg} \) is also
equal to the fraction of the total length of the open-closed field line boundary occupied by the nightside merging gap.

Examining Eq. (5.1) we can see that if $\Delta A = 0$ for a particular interval (as is true overall for the intervals considered here) then the magnitudes of the mean dayside and nightside reconnection rates are both equal to the mean polar cap voltage $\langle V_{pc} \rangle$. On the other hand, if the polar cap area contracts during the interval such that $\Delta A < 0$, then the magnitude of the nightside reconnection rate will be greater than $\langle V_{pc} \rangle$, while that of the dayside reconnection rate will be less than $\langle V_{pc} \rangle$. An inconsistency occurs if the magnitude of the second term in Eq. (5.1b) exceeds the first, implying that $\langle \Phi_d \rangle$ is negative, contrary to assumption. If this is found to be the case, the implication is that the closed flux is not distributed uniformly around the boundary by the flow as assumed. However, for the events analysed here a more stringent condition on $\langle \Phi_d \rangle$ may be considered, since it has been argued in the present case that over the interval as a whole the dayside and nightside reconnection rates must be in approximate balance. Thus in the absence of an unlikely anti-correlation between the dayside and nightside reconnection rates, the value of $\langle \Phi_d \rangle$ during the nightside burst events should not generally differ greatly from the polar cap voltage averaged over the whole interval. For the first 6 h interval considered here (on 2 Dec) the transpolar voltage averaged over the whole interval determined from the SuperDARN data was $\sim$35 kV, while for the second (on 14/15 Dec) it was $\sim$28 kV (see Figs. 5.8 and 5.15).

Eqs. (5.1a) and (5.1b) are now used to estimate the reconnection rates during the first burst interval. As discussed above, this is the only burst of the three studied in detail here in which the radar data clearly define the flow reversal boundary. If we examine these equations it is clear that some of the parameters on the right hand sides are determined by the data better than others. In particular, the mean polar cap voltage $\langle V_{pc} \rangle$ during the burst is reasonably well determined from the SuperDARN data, while the net area swept out by the open-closed field line boundary $\Delta A$ and the fraction $f_{mg}$ of that associated with the nightside merging gap are not so well determined. With regard to $f_{mg}$, values can be estimated by inspection of the flow patterns during the burst interval. It has been argued
above that the maximum and minimum in the electric potential lie at either end of the nightside merging gap under the nightside ‘burst’ conditions investigated here. Identification of the location of the foci of the flow cells therefore provides an indication of the magnetic local time extent of the merging gap, from which $f_{mg}$ can be estimated. However, with regard to the change in polar cap area, it has been possible to make only an approximate determination of the poleward displacement of the boundary, quantised in 1° latitude steps, in one nightside local time sector, where a clearly-defined flow reversal is evident. As in Chapter 4, the approach here has therefore been to look at the sensitivity of the results to these less-well determined parameters.

What has been done (in effect) is to plot a contour map of $\langle \Phi_\mu \rangle$ and $\langle \Phi_d \rangle$ on the $f_{mg} - \Delta A$ plane, and to delineate regions of consistency both with the rather roughly-obtained limits on these latter parameters, and on $\langle \Phi_d \rangle$ as discussed above. However, rather than use $\Delta A$ directly, the latitude displacement of the boundary in the local time sector in which this has been determined via the analysis presented above (in Fig. 5.10) has been used. From this displacement the areas $\Delta A$ have been calculated by extrapolation of the initial and final boundary positions to other local times. Specifically it has been assumed for simplicity (and in accordance with the Cowley-Lockwood paradigm) that the initial and final boundaries are circles drawn about a common centre. The chosen centre is displaced from the magnetic pole by 2° of magnetic latitude towards the nightside, this also being the chosen ‘centre’ of the spherical harmonic analysis of the SuperDARN data. Examination of the flow patterns overall indicates that this is a very reasonable choice, and that no substantial improvement would result from attempting to use some more complicated boundary shape.

Results for the burst occurring during 0246-0315 UT on 2 Dec are shown in Fig. 5.19, based on the data shown in Fig. 5.10. Here reconnection rate contours are plotted on the $f_{mg} - \Delta \Lambda_B$ plane, where $f_{mg}$ is shown on the vertical axis, and the displacement of the magnetic latitude of the flow reversal boundary $\Delta \Lambda_B$ during the event is shown on the horizontal axis. From the latter parameter the change in area of the polar cap has then been calculated according to the above algorithm, starting from an initial boundary position at
Figure 5.19 Reconnection rate contours plotted on the $f_{mg}$-$\Delta \Lambda_B$ plane, where the fraction of the open-closed field line boundary occupied by the nightside merging gap, $f_{mg}$, is shown on the vertical axis, and the poleward displacement of the magnetic latitude of the nightside flow reversal boundary $\Delta \Lambda_B$ during the event is shown on the horizontal axis. The dark-shaded area in the bottom right corner of each plot represents an area of inconsistent results where the dayside reconnection rate becomes negative. The horizontal dotted lines mark the likely range of $f_{mg}$ for the event (obtained from the SuperDARN maps), with the exterior region shown shaded. Also shaded is the region of unreasonable dayside reconnection rates as discussed in the text. The remaining unshaded area corresponds to the region of solutions that conforms to all these constraints. These results are plotted for the 0300 UT burst on 2 Dec.
\( \Lambda_B = 76^\circ \) in this case (Fig. 5.10), so that \( \Delta A \) becomes increasingly negative as we move from left to right across the plot. For this event a 1° poleward displacement of the boundary in the 2100 MLT sector corresponds to a flux closure of \( B_i \Delta A = -0.6 \times 10^8 \) Wb, while 2° corresponds to \(-1.1 \times 10^8 \) Wb and 3° to \(-1.5 \times 10^8 \) Wb. Using a value of the averaged transpolar voltage of \( \langle V_{PC} \rangle = 42 \) kV for the interval, determined from the data shown in Fig. 5.10, contours of \( \langle \Phi_n \rangle \) and \( \langle \Phi_d \rangle \) have been plotted, shown by the solid and dashed lines, respectively. At the left-hand edge of the plot we have \( \Delta \Lambda_B = 0 \) (and \( \Delta A = 0 \)), so that at this limit Eqs. (5.1a) and (5.1b) give \( \langle \Phi_d \rangle = \langle \Phi_n \rangle = \langle V_{PC} \rangle \), as discussed above. We also have \( \langle \Phi_n \rangle = -\langle V_{PC} \rangle \) along the bottom edge of the plot where \( f_{mg} = 0 \), and \( \langle \Phi_d \rangle = \langle V_{PC} \rangle \) along the top edge of the plot where \( f_{mg} = 1 \). Away from these respective boundaries \( \langle \Phi_n \rangle \) becomes increasingly negative as \( f_{mg} \) and \( \Delta \Lambda_B \) both increase, while \( \langle \Phi_d \rangle \) drops to smaller values as \( f_{mg} \) decreases and \( \Delta \Lambda_B \) increases. Eventually \( \langle \Phi_d \rangle \) becomes negative in the dark-shaded area in the bottom right corner of the plot, this representing an area of inconsistent results (as discussed above) when \( (1 - f_{mg}) \Delta A \) becomes too negative.

Next, the likely ranges of the controlling parameters, and the consequent likely range of values of the reconnection rates have been considered. First, examination of the flow maps during the interval indicates that the nightside merging line is relatively extended, with \( f_{mg} \) lying in the range \(-0.35 \) to \(-0.65 \), corresponding to \(-0.15 \) either side of the average value for the duration of the burst. This range is marked by the horizontal dotted lines, with the exterior region shown shaded. Second, according to the above argument, we can reasonably expect the dayside reconnection rate to have lain in the range \(-30 \) to \(-40 \) kV, corresponding to \(-5 \) kV on either side of the total transpolar voltage averaged over the whole 6 h interval of observations. The region outside these limits is also shaded. The remaining unshaded area then represents the solutions which are compatible with both of these constraints. The location of this area first suggests an overall poleward boundary displacement between \(-0.5^\circ \) and \(-1^\circ \), reasonably consistent with the \(-1^\circ \) displacement inferred in Fig. 10. It also suggests nightside reconnection rates of \(-45-60 \) kV, which thus exceed concurrent dayside rates by \(-10-20 \) kV.
The implication of these results is that during the burst interval examined here, the nightside reconnection rate exceeded the dayside reconnection rate by a factor of ~0.5. Under conditions of weak northward-directed but $B_y$-dominated IMF, therefore, it appears that the flow continues to be dominated by Dungey-cycle flow as it is during intervals of southward-directed IMF, and the 'return' flow from the tail is often bursty and sporadic. However, the data also show that these bursts are not accompanied by phenomena characteristic of substorms, such as enhanced auroral zone conductivities, magnetic bays, Pi2s, or geostationary energetic particle injections. It seems likely that the impulsive phenomena concerned, while possibly being related physically to substorms, were taking place considerably further down the tail than is typical of more strongly-driven intervals.

5.4 Summary and conclusions

In this chapter the ionospheric flow and magnetic disturbance which occurred during two 6 h near-steady intervals of northward, but $B_y$-dominated, IMF have been discussed. During the first interval, on 2 December 1999, the average IMF clock angle was ~60° and the field strength was ~10 nT. During the second interval, on 14/15 December 1999, the average IMF clock angle was ~50°, and the field strength was ~7 nT. Both sets of conditions gave rise to similar continuous flows in the polar ionosphere, with a highly asymmetric twin-vortex pattern being observed, consistent with directly driven Dungey-cycle convection. This flow was slightly weaker during the second interval compared with the first (the mean transpolar voltage was 29 kV compared to 35 kV), possibly due to the reduced IMF clock angle and field strength. On shorter time scales, however, the flow exhibited intervals of strong variability in the nightside ionosphere, which differed slightly in nature between the two intervals. During the 2 December interval, ~1000 m s⁻¹ bursts of flow were observed in the midnight sector, lasting a few tens of minutes and recurring every hour or so. They were accompanied by weak magnetic signatures (~10 nT) and low amplitude Pi2-band (5-50 mHz) activity, although it is not clear that either were directly associated. During the 14/15 December interval, the bursts were observed to be less regular, with only one discernable event occurring during the first half of the interval. During the second half the
bursts become more frequent, but appear to be less distinct from one another than those observed during the first interval.

Over the entire 6 h of each interval, it was observed that the size of the convection pattern remained relatively constant. This implies that tail reconnection was ongoing, at an average rate approximately equal to that at the dayside magnetopause. However, the nightside flow observations then indicate that this reconnection typically was not steady, but underwent sporadic enhancements giving rise to the flow burst intervals. This is indicated by the fact that each burst was accompanied by an enhancement in the total transpolar voltage, and in one example where the flow reversal boundary was well observed, appeared to be coincident with a small (~1°) contraction of the polar cap boundary. These bursts are therefore likely to be an ionospheric manifestation of convective transport away from a distant tail reconnection site. A simple model of this process, based on the Cowley and Lockwood (1992) picture of reconnection-associated flow excitation, has enabled an estimate of the nightside reconnection rate associated with one of these burst intervals to be made, based on assumed limits on the dayside rate. It is estimated that, during this burst, the nightside reconnection rate was elevated typically to values ~45-60 kV, thus exceeding the likely concurrent dayside reconnection rates of ~30-40 kV by a factor of ~1.5. Bearing in mind the fact that over the full 6 h of each interval, the polar cap remains relatively constant in size, this also implies a 'non-burst' nightside reconnection rate of ~20-25 kV. Whilst not manifest as substorms, these discrete bursts of enhanced tail reconnection seem clearly to be a related phenomenon occurring, as suggested above, much further down-tail. In effect, these results have demonstrated that whilst under conditions of southward IMF, the Dungey cycle will usually be manifest as the substorm cycle, the two are not, in fact, synonymous. Intermediate interplanetary conditions exist, such as those considered here, in which the Dungey cycle continues to drive the system, but without evidence of substorms being observed (though tail activity appears still to be pulsed on ~1 h time scales). The question remains as to exactly what range of interplanetary conditions gives rise to a tail response of this nature. The corresponding picture for positive B_y-dominated IMF also needs to be investigated. These questions, however, remain the subject of future work.
CHAPTER 6

Future directions

This thesis has been concerned with one of the major themes of research in magnetospheric physics, that of the large-scale flow driven by the magnetosphere’s interaction with the solar wind. Although considerable progress has been made in over thirty years of intensive study, such that for example, the overall nature of the flow and its dependence on the IMF is now well established, a number of significant issues remain. Some of these relate to the initiating processes at the magnetopause. For example, the central issue of the pulsed nature of dayside reconnection, leading to FTEs, has yet to be understood. Others relate to the role of tail processes in magnetospheric convection, and it is this area which has been focussed on in this thesis. Specifically, detailed results have been presented from two studies which have investigated flow excitation during substorms, and nightside flows during intervals of intermediate IMF clock angles. Each of these studies has provided specific results detailed in the previous chapters. However, they also highlight the existence of further unanswered questions, and point the way towards several future studies. The sections below consider some of the next steps that now need to be taken, and briefly review the results of some pilot studies that have already been undertaken.

6.1 Flow during magnetospheric substorms

As has already been discussed in Chapter 4, during intervals of southward IMF, the return of open flux from the tail lobes is presumed to be dominated by intervals of reconnection which take place during the expansion and recovery phases of substorms. As also pointed out, if this is the case then substorms ought also to excite flows in the high-latitude nightside ionosphere, in a similar manner to the excitation of dayside flows during FTEs. In
Chapter 4 clear evidence has been presented for such excitation during a particularly well-observed isolated high-latitude substorm which occurred during an interval of northward IMF. However, as discussed in both Chapters 2 and 4, observational evidence for this phenomenon is not always present, and it is as yet unclear why this is so. It could just be a result of observational constraints, such as those discussed in Chapter 4, which were circumvented owing to the fortuitous circumstances under which this substorm occurred. On the other hand, there may be geophysical factors which influence whether flow excitation is going to occur (or at least to what extent it will occur), that need to be taken into consideration. Either way it is clear that an in-depth study of a large number of events, making use of the increasing compliment of instruments available both on the ground and in space, should follow.

A brief pilot study of this nature has already been undertaken, via an examination of SuperDARN radar data from December 2001, during which period 8 radars were operational in the northern hemisphere. These data alone provide ~10 examples for future study, three of which are briefly considered here. Fig. 6.1 shows magnetic $H$-component data from the Greenland west coast magnetometer chain for the three substorms which occurred on 06, 08, and 15 Dec 2001. The approximate time of substorm onset in each case is indicated by the vertical dotted lines. Fig. 6.2 then shows four selected SuperDARN flow maps for each of these substorms, which show the development of the flows from pre-onset through to recovery. Although the flow excitation is not as distinct as that observed during the substorm studied in Chapter 4, there is nevertheless a clear enhancement to the pre-existing twin-vortex flow, and corresponding transpolar voltage, during the expansion phase in each case. This can be seen, for example, in the 0112 UT map in Fig. 6.2 (a), the 0102 UT map in (b), and the 0320 UT map in (c). Whilst the exact nature of flow excitation during substorms is therefore quite variable, these data do suggest that it is nevertheless a common phenomenon. Further investigation of the cause of this variability is, however, clearly warranted.
Figure 6.1 Greenland west coast magnetometer H-component data for (a) 0100-0200 UT on 06 Dec 2001, (b) 0000-0200 UT on 08 Dec 2001, and (c) 0300-0500 UT on 15 Dec 2001. The horizontal dotted lines indicate the baseline for each of the stations (indicated on the left-hand axis by their respective identifier codes), and the vertical dotted lines give an approximate indication of substorm onset times. Also shown on the left-hand axis is the scale (in nT) of each panel, and shown on the right-hand axis is the CGM latitude of each station.
Figure 6.2a Streamlines and vectors of the ionospheric flow derived from eight-radar SuperDARN velocity measurements are shown on a geomagnetic grid, obtained from the 'Map-Potential' algorithm (see Chapter 2). Four selected flow maps are shown for the substorm interval on 06 Dec 2001. Indicated at the bottom of each map is the total transpolar voltage $V_{PC}$ (left-hand corner), and the direction and magnitude (in the $y$-$z$ plane) of the IMF (right-hand corner). In the top right-hand corner is the flow model employed to stabilise the potential solution in regions where no data are available, obtained from the statistical study of Ruohoniemi and Greenwald (1996).
Figure 6.2b As Fig. 6.2a but for the substorm interval on 08 Dec 2001.
Figure 6.2c As Fig. 6.2a but for the substorm interval on 15 Dec 2001.
6.2 Flows for intermediate IMF clock angles

The results described above in Chapter 5 show that when the IMF turns northward the substorm cycle dies away. Nevertheless, the Dungey flow cycle has been found to persist in the ionosphere over many hours at intermediate clock angles $|\theta| \sim 50^\circ$ to $60^\circ$ when the IMF is northward but dominated by $B_y$. While there are no substorms under these conditions, there is direct evidence for 'flow bursts' in the nightside ionosphere, which are suggested as being related to bursts of reconnection in the distant tail. However, the results presented in Chapter 5 were obtained during extended intervals of negative IMF $B_y$, a preliminary search having failed to find any corresponding intervals on positive $B_y$ in data then available. An immediate task, therefore, is to examine more recent data for such positive $B_y$ intervals.

Again, a pilot study of this nature has already been undertaken, which has revealed at least one such interval. This occurred in November 2001, during which the IMF clock angle remained relatively steady at $\sim 45^\circ$ for $\sim 16$ hours. Some examples of the flow are shown in Fig. 6.3, which consists of 12 selected maps from the interval 1900-1100 UT on 01/02 November 2001. An examination of the flow data reveals the continuous presence of Dungey-cycle flow as for the intervals described in Chapter 5. Evidence of dayside driving of the flows is particularly evident in the 1900 UT map from the start of the interval, and in the 0610 UT map from towards the end. As expected, these flows also have the opposite sense of $B_y$-related asymmetry to the earlier intervals as evidenced, for example, in the 0200 UT map. Here the flow pattern more resembles the southern hemisphere data for the $B_y$ negative case. In addition, evidence of burst-like flows were also observed on the nightside. Examples of these can be seen in the 2000, 0252, and 0734 UT maps, and show similar characteristics to the bursts studied in Chapter 5.

As with the $B_y$ negative intervals, a preliminary inspection of relevant magnetometer data suggests that there is essentially no magnetic activity in association with the flows described above. It would therefore appear that the bursty nightside flows may well be as a result of a similar phenomenon to the tail reconnection bursts suggested in Chapter 5. Clearly,
Figure 6.3 Streamlines and vectors of the ionospheric flow derived from eight-radar SuperDARN velocity measurements are shown in the same format as in Fig. 6.2. Twelve maps are shown in total from the interval 1900 UT on 01 Nov to 1100 UT on 02 Nov, 2001.
Figure 6.3 cont. Streamlines and vectors of the ionospheric flow derived from eight-radar SuperDARN velocity measurements are shown in the same format as in Fig. 6.2. Twelve maps are shown in total from the interval 1900 UT on 01 Nov to 1100 UT on 02 Nov, 2001.
Figure 6.3 cont. Streamlines and vectors of the ionospheric flow derived from eight-radar SuperDARN velocity measurements are shown in the same format as in Fig. 6.2. Twelve maps are shown in total from the interval 1900 UT on 01 Nov to 1100 UT on 02 Nov, 2001.
however, this is a study which needs to be carried forward in future work. Beyond this, the range of IMF clock angles for which this type of behaviour occurs needs to be examined, as well as how it interfaces with the substorm regime for larger clock angles, and with the 'lobe convection' regime at smaller clock angles.

Overall, therefore, while the work presented in this thesis has answered a number of significant questions in solar terrestrial physics, it also suggests a number of new lines of enquiry which may profitably be pursued in future work.
Appendix

APPENDIX

from Adams and Lloyd, 1990
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