The Cause of Magnetic
Disturbances in the Earth’s Ionosphere

Thesis submitted for the degree of
Doctor of Philosophy
at the University of Leicester

by

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September 1994
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ABSTRACT

This thesis studies the phenomenon of the magnetic storm, which is a global disturbance of the Earth's magnetic field and is defined in this thesis as an interval during which the Dst index falls below -50 nT for four consecutive hours. Storms are classified as either storm sudden commencements (SSCs; all storms which are initiated by a sudden impulse recorded by ground magnetometer stations) and storm gradual commencements (SGCs; all other storms). A superposed epoch analysis of solar wind plasma, interplanetary magnetic field (IMF) and magnetic indices AL, Kp and Dst has been undertaken for 538 storms identified between 1963 and 1991. The superposed epoch signature of the interplanetary medium during SSCs is similar to the signature of coronal mass ejections, whereas the corresponding superposed epoch signature of SGCs is similar to the signature of a high speed/low speed coronal stream interface. A statistical study on the occurrence of the 538 identified storms has also been undertaken. The previously observed semi-annual variation in the occurrence of magnetic storms is shown to apply to SGC events only. Universal time (UT) variations in the onset times of SGCs have been observed. A UT variation has also been observed in the time-of-peak activity in the Am and Dst indices during storms. A case study of the ionospheric convection during the magnetic storm of March 20–21, 1990 has been undertaken. The response time of the ionospheric convection to changes of the IMF at the magnetopause associated with the SSC was a factor of two quicker than previous observations under normal solar wind conditions. A latitudinal dependence in the convection response time was also observed. Reconfigurations of the nightside convection pattern in response to substorm expansion phase onsets were observed implying that the nightside convection pattern can be dominated by substorm activity.
This thesis is dedicated to

*Mum* and *Dad*
Acknowledgements

Sincere thanks are due to many people who have helped me over the last three years. In particular I would like to thank the following: Professor Tudor Jones for his help and guidance whilst I was an undergraduate, for the opportunity to research for my PhD in the Ionospheric Physics Group at Leicester University and for his constructive comments on this manuscript; Dr. Mark Lester, my supervisor, and Dr. Tim Yeoman for their advice, patience and constructive criticism at all stages over the last three years.

I would also like to thank the following people:

Dr. David Kerridge, my industrial supervisor, and Dr. Toby Clark at the British Geological Survey (CASE collaborating institute) for their helpful discussions and hospitality during my visits to Edinburgh.

Past and present members of the Ionospheric Physics Group at Leicester for their help, encouragement and companionship over the last three years, in particular:

Dr. Chris Thomas, Nigel Wade, and Andrew Stone for maintenance of the groups computer systems, without which it would not have been possible to undertake the research.

Steve Milan, Brian Shand and Richard Beard for use of their computer software.

Jackie Davies for the ionospheric physics song and several figures to be found in this thesis.

Dr. Terry Robinson, Dr. Alan Stocker, Dr. Paul Eglitis, Dr. Eric Bradshaw, Dr. Martin Popple and Dr. Farideh Honary for their assistance and encouragement.

Paul Rylah for many helpful discussions.
Holly Paisey for invaluable advice on insomnia.

Carol and Kathy Charles for the delicious cakes.

John (the Accountant) Sharpe who specifically requested to be acknowledged and Graeme Holdsworth who is too polite to ask.

All members of the Geomagnetism group at the British Geological Survey in Edinburgh for their friendly welcome and assistance during my visits there.

I would like to thank the following people and institutions for the supply of the enormous data sets from which the analysis of this thesis is derived. Matthew Wild at the World Data Centre for putting up with my numerous data requests. Dr. David Orr for the SAMNET data, Dr. I. Solovyev for Yakutsk magnetometer data, Dr. E. P. Kharin at WDC B2 for other Russian magnetometer data and Drs. Delores Knipp and Barbara Emery for digitising and preparing the Russian data. The EISCAT Scientific Association is supported by Centre National de la Recherche Scientifique of France, Suomen Akatemia of Finland, Max-Planck-Gesellschaft of Germany, Norges Almenvitenskapelige Forskningsråd of Norway, Naturvetenskapliga Forskningsrådet of Sweden and the Science and Engineering Research Council of the United Kingdom. Dr. Mike Ruohoniemi for providing the Goose Bay radar data. Dr. Mike Buonsanto for the Millstone Hill radar data. Dr. John Kelly for the Sondrestrom radar data. Dr. Jim Scali for the Digisonde data. Dr. A. J. Lazarus for the IMP–8 IMF data and Dr. Ron Lepping for the IMP–8 solar plasma data.

I would like to thank Profs. K. A. Pounds and T. B. Jones (again) for supplying facilities in the Department (H. o. D.'s).

Finally I would like to thank the SERC in association with the British Geological Survey for their financial support over the last three years.
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**Glossary**

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<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_{sw}$</td>
<td>Solar wind density</td>
</tr>
<tr>
<td>$\phi_{pc}$</td>
<td>Cross polar cap potential</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Acute angle between Earth-Sun line and geomagnetic dipole axis</td>
</tr>
<tr>
<td>$\chi^2$</td>
<td>Chi-square statistical test</td>
</tr>
<tr>
<td>$AL$</td>
<td>Auroral (westward electrojet) magnetic index</td>
</tr>
<tr>
<td>$Am$</td>
<td>Mid-latitude magnetic activity index</td>
</tr>
<tr>
<td>$B$</td>
<td>Magnetic field</td>
</tr>
<tr>
<td>BGS</td>
<td>British Geological Survey</td>
</tr>
<tr>
<td>CME</td>
<td>Coronal mass ejection</td>
</tr>
<tr>
<td>$D$</td>
<td>East-west component of geomagnetic field</td>
</tr>
<tr>
<td>$Dst$</td>
<td>Ring current magnetic field index</td>
</tr>
<tr>
<td>$E$</td>
<td>Electric field</td>
</tr>
<tr>
<td>EISCAT</td>
<td>European Incoherent SCATter radar facility</td>
</tr>
<tr>
<td>f-o-v</td>
<td>field-of-view</td>
</tr>
<tr>
<td>GB</td>
<td>Goose Bay (coherent radar or digisonde)</td>
</tr>
<tr>
<td>GSE</td>
<td>Solar geocentric ecliptic coordinate system</td>
</tr>
<tr>
<td>GSM</td>
<td>Solar geocentric magnetic coordinate system</td>
</tr>
<tr>
<td>$H$</td>
<td>North-south component of geomagnetic field</td>
</tr>
<tr>
<td>IGRF</td>
<td>International geomagnetic reference field</td>
</tr>
<tr>
<td>IMF</td>
<td>Interplanetary magnetic field</td>
</tr>
<tr>
<td>$K$</td>
<td>Magnetic activity index from a single station</td>
</tr>
<tr>
<td>$Kp$</td>
<td>Planetary magnetic activity index</td>
</tr>
<tr>
<td>l-o-s</td>
<td>line-of-sight</td>
</tr>
<tr>
<td>MH</td>
<td>Millstone Hill (incoherent radar or digisonde)</td>
</tr>
<tr>
<td>MLT</td>
<td>Magnetic local time</td>
</tr>
<tr>
<td>PCB</td>
<td>Polar cap boundary</td>
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<tr>
<td>$P_{sw}$</td>
<td>Solar wind dynamic pressure</td>
</tr>
<tr>
<td>$R_E$</td>
<td>Radius of the Earth</td>
</tr>
</tbody>
</table>
SABRE  Sweden and Britain Radar-aurora Experiment
SAMNET  Sub-Auroral Magnetometer NETwork
SC  Sudden Commencement
SGC  Storm gradual commencement
SSC  Storm sudden commencement
$T_{sw}$  Solar wind temperature
USGS  United States Geological Survey
UT  Universal time
$U(t)$  Energy transfer rate between solar wind and magnetosphere
$v_{pc}$  Polar cap expansion velocity
$v_{sw}$  Solar wind velocity
Sing a song of substorms
plasmoids in the sky
Reconnecting field lines
all convecting by
When the field is open
ions start to flow
Particle injection
makes aurora glow

Jackie Davies and the members of G55
1993
CHAPTER 1

Introductory and Background Material

1.1 Introduction
This thesis investigates the phenomenon of the geomagnetic storm. A geomagnetic storm (also referred to in this thesis as a "magnetic storm", or simply as a "storm") is a global disturbance of the Earth’s magnetic field which results in large perturbations measured by magnetometers on the Earth’s surface. A detailed review of magnetic storms is presented in Chapter 2. This chapter introduces basic solar terrestrial background material which will enhance the reader’s understanding of later chapters.

1.2 The Sun and Geospace

1.2.1 The Sun
The Sun is the primary source of all geomagnetic activity, and it is therefore appropriate to begin this thesis with a brief résumé of the Sun. The Sun is a hot ball of plasma of mass \( \sim 10^{32} \) kg, with a core temperature of \( \sim 10^7 \) K, and is comprised of \( \sim 75\% \) hydrogen with the remaining 25% primarily of helium [see e.g. Priest, 1985]. A schematic illustration of the various layers of the Sun is presented in Figure 1.1. The visible surface of the Sun, the photosphere, has a radius of \( 6.96 \times 10^8 \) m and a temperature of \( \sim 6000 \) K. The Sun is surrounded by a hot, rarefied gas called the corona, with typical densities of \( \sim 10^8 \) m\(^{-3} \) and temperatures reaching \( 2 \times 10^6 \) K. The Sun also has an active magnetic field, which reverses polarity about every 11 years. During this 11 year cycle, cool spots appear in the Sun’s photosphere. These sunspots form in pairs and are of opposite magnetic polarity. In the early part of the solar cycle, when sunspots are relatively scarce in number and appear near the solar equator, the Sun’s field is near dipolar. The solar magnetic field is deformed as the solar cycle progresses and sunspots appear at higher latitudes and in greater numbers. Closed loops of magnetic flux may join a sunspot pair. Particles trapped...
Figure 1.1 Schematic illustration of the Sun.
in the closed loops can be seen from the Earth as prominences.

1.2.2 The Solar Wind and the Interplanetary Magnetic Field

The solar wind is the expanding corona of the Sun, although the details of the particle acceleration are not known. The solar wind plasma has a similar composition to the Sun, comprising of ~95% hydrogen and the remainder mainly helium. At 1 Astronomical Unit (AU) typical parameters for the solar wind velocity ($v_w$), particle density ($n_p$) and temperature ($T_w$) are 300 km s$^{-1}$ to 600 km s$^{-1}$, $5 \times 10^6$ m$^{-3}$ to $15 \times 10^6$ m$^{-3}$ and $5 \times 10^6$ K to $2 \times 10^7$ K respectively [see e.g. Gosling et al., 1976; King, 1986].

Associated with the solar wind is the interplanetary magnetic field (IMF) which is the residue of the solar magnetic field. The magnetic Reynolds number ($R_m$) is a measure of the ratio of the convection term to the magnetic diffusion term in a time varying magnetic field and is equal to $\mu_0 \sigma v L$, where $\mu_0$ is the permeability of free space, $\sigma$ is the conductivity of the medium, $v$ is the characteristic speed of the plasma and $L$ is the characteristic size of the system. For the solar wind/IMF system with a scale size of ~2 solar radii, $R_m$ is of order $10^{11}$, thus convection dominates, and the IMF and solar wind flow are said to be “frozen” together. As a consequence of “frozen in” flow, the IMF is transported with the solar wind as it expands into the solar system. At 1 AU the IMF has a typical magnitude of ~5 nT but can exceed 30 nT during disturbed periods. Due to the rotation of the Sun successive particles from a particular heliospheric longitude will form an Archimedean spiral (sometimes referred to as the Parker spiral or as the “garden hose effect”). Since the IMF is frozen to the solar wind flow it too is wound into the Parker spiral. A current sheet is formed approximately on the ecliptic plane between the oppositely directed field lines of the southern and northern solar hemispheres. As the Earth passes from one side of the sheet to the other, long periods of stable radial magnetic field are interrupted by sudden reversals of the field. This creates a sector structure in the IMF, as illustrated in Figure 1.2 where 4 sectors are present. At solar minimum, when the Sun’s field is more dipolar, the current sheet is relatively undisturbed and a two cell sector structure is dominant. As the solar cycle progresses the current sheet is distorted from planer such that the sector structure breaks down into four or even six sectors and is generally unstructured near solar maximum [e.g. Yeoman et al., 1990]. Although the
Figure 1.2 Illustration of the interplanetary sector structure. The neutral sheet is curved in the XZ (GSE) plane such that the Earth passes from sectors of predominately away field lines into regions of predominantly toward field.
radial (X) and dawn/dusk (Y) components may be of consistent polarity for several days, the north/south (Z) component polarity typically varies on a time scale of ~1 h.

1.2.3 The Magnetosphere

Figure 1.3 is a schematic illustration of the Earth's magnetosphere [see e.g. the review by Vasyliunas, 1983]. Since the particle speed (>300 km s⁻¹) is greater than the Alfvén speed (~150 km s⁻¹) in the solar wind a shock front is generated between 15 R_E to 18 R_E upstream of the Earth, known as the bow shock. Again, convection dominates over the magnetic diffusion in the magnetosphere, with R_m~10¹⁶ (scale length ~1 R_E) resulting in field and flow once more frozen together. Since, to a first approximation, both the solar wind and the magnetosphere are subject to frozen in flow neither system can penetrate the other, thus the solar wind is swept around the geomagnetic cavity forming the magnetosheath with a typical number density of 10⁶–10⁷ m⁻³. The Earth's otherwise dipolar magnetic field, bounded by the magnetopause typically between ~9 R_E to 11 R_E, is distorted by the magnetic pressure from the charged particles in the solar wind such that it is compressed on the dayside and stretched out on the nightside to form the magnetotail. Although the down-stream extent of the magnetotail is not known, spacecraft have detected the magnetotail out as far as 1000 R_E from the Earth.

The plasmasphere is a region of relatively dense (10⁶ m⁻³) low temperature plasma which extends to ~4 R_E. The plasmasphere is threaded by closed magnetic flux and consists predominantly of co-rotating trapped particles originating mostly from the ionosphere. The Van Allen radiation belts are comprised of high energy charged particles trapped in the magnetic bottle provided by the Earth's dipole field, with peak particle densities at ~2 R_E and ~4 R_E. In practice, there is coupling between the magnetosphere and solar wind at high latitudes (usually greater than 70°), in which the geomagnetic field connects directly to the IMF [see Section 1.3.2]. These regions of open flux are often defined as the polar caps, a definition which is adopted throughout this thesis. At the dayside boundaries between open and closed field lines in the northern and southern polar caps are the polar cusps (or clefts) in which solar wind plasma may penetrate the magnetopause and flow down into the ionosphere.
Figure 1.3  Illustration of the various regions of the geomagnetic field.
1.2.4 The Ionosphere

The terrestrial ionosphere is a region between altitudes ~60 km and 1000 km, with the lower boundary defined as the height at which radio propagation can be significantly affected (Figure 1.4). Figure 1.4 also illustrates electron density profiles as a function of height for the ionosphere. The density profile classification separates the ionosphere into four zones; the D, E, F1 and F2 regions [see reviews by Schunk, 1983; Rishbeth, 1988].

The D region extends from ~50 km to ~90 km. The gyro frequency of both electrons and ions are very much less than the collision frequency between particles and the plasma is dominated by collisions between electrons, ions and neutral particles. Therefore in the D layer both electrons and ions move with the neutral wind and chemistry plays an important role in the behaviour of this region. The detailed physics of this layer are beyond the scope of this thesis.

The E region extends from ~90 km to ~160 km and is effectively a transition region. At low altitudes, near 80 km, the electron gyro frequency, $\Omega_e$, is of the same order as the collision frequency between electrons and neutrals, $\nu_{en}$, such that electrons are in the process of decoupling from the neutral wind and ions. At ~110 km the electrons are fully decoupled and move with the $E \times B$ drift allowing the generation of strong electric currents. Since the electrons and ions move independently the E region has a high conductivity perpendicular to $E$ and $B$. The resulting currents are known as Hall currents. By ~130 km in altitude, the ion gyro frequency, $\Omega_i$, is of the same order as the collision frequency between the ions and neutral atoms, $\nu_{in}$, and thus the ions are in the process of decoupling from the neutrals.

The F Region lies at altitudes greater than ~160 km, comprising of the main peak of electron production and corresponds to the ionisation of O and N2. The ions are fully decoupled by 160 km, where both electrons and ions move with the $E \times B$ drift. Since the $E \times B$ drift moves electrons and ions in the same direction no significant electric currents will be generated at this altitude even though there may be considerable bulk movement of charged particles. The dominant conductivities in the F region are parallel to $E$ with the resulting currents known as Pedersen currents. Bifurcation of the F region may take place during the day to form a double peak in the density profile, subdividing the layer into the F1 and F2 layers due to differences in chemistry at varying heights.
Figure 1.4 Graph illustrating the various regions of the ionosphere and neutral atmosphere.
Probably the best known feature of the high latitude ionosphere, the aurora is a brightening of the night sky arising from the precipitation of high energy electrons, which excite neutral atoms into metastable states. It is the visible photons emitted by the decay of these excited atoms which give rise to the auroral displays. The region of visible aurora is a region near the equatorward boundary of open magnetic flux in the north pole and forms a closed loop known as the auroral oval.

1.3 Solar Wind/Magnetospheric Coupling and Magnetospheric Dynamics

1.3.1 Viscous Interaction

Two models have been proposed to describe the coupling processes between the solar wind and the geomagnetic field. The first, proposed by Axford and Hines in 1961, is known as the closed, or viscous interaction, model. Figure 1.5a illustrates the interaction between the solar wind and the magnetosphere upon strict application of the frozen in limit. In this model momentum is transferred from the solar wind into the magnetosphere by a so-called viscous interaction, although the exact mechanism of such an interaction is not certain. The particle density at the magnetopause is too low for collisions to be significant, but the coupling process could be initiated by the generation of irregularities such as the Kelvin-Helmholtz instability which is analogous to the momentum transfer from waves generated by wind sweeping over the ocean. In response to the transfer of momentum at the magnetopause, plasma is carried antisunward toward the geomagnetic tail. This results in a pressure difference between the day and the night sides such that plasma from the nightside convects toward the dayside at lower latitudes generating a closed loop, resulting in a twin cell convection pattern which maps down into the ionosphere.

1.3.2 Magnetic Reconnection

The magnetohydrodynamic (MHD) theory which describes the large scale properties and behaviour of the solar wind and magnetosphere requires relatively large scale lengths. On scale lengths of the magnetosphere/IMF boundary (~100 km), however, the MHD approximation breaks down and particles may diffuse across the boundary between the
Figure 1.5 Magnetospheric models of the interaction between the geomagnetic field and the IMF based on: a) strict application of the frozen in limit of Axford and Hines [1961]; and b) the reconnection model proposed by Dungey [1961].
two plasmas separated by regions of oppositely directed magnetic field. Such a diffusion results in the flow of a $\mathbf{v} \times \mathbf{B}$ current and annihilation of the magnetic field at a neutral line then occurs. The field lines between the separate plasma regions will reconnect either side of the neutral line about which the annihilation takes place (Dungey, 1961).

Figure 1.5b illustrates the process between the magnetosphere and the IMF subject to reconnection at the dayside magnetopause. If the IMF has a southward component a neutral line will emerge at the subsolar magnetopause, resulting in reconnection of the magnetic fields between the two systems. Previously closed magnetic field lines of the geomagnetic field will become “open”, connecting to the IMF. This reconnecting region maps down into the ionosphere. Magnetic tension in response to the curvature in the reconnected field line causes the newly opened field to straighten. The field lines are then dragged antisunward across the polar cap by the rapidly streaming “frozen in” solar wind plasma. Magnetic flux is thus eroded from the dayside and accumulates on the nightside. Reconnection also occurs in the magnetotail, returning closed magnetic flux and plasma to the magnetosphere, which convects to the dayside in a return flow at auroral and subauroral latitudes. A convection pattern is generated in the magnetosphere which is mapped down into the ionosphere as a twin-cell pattern (Figure 1.6). The final convection pattern is asymmetric resulting both from corotation with the Earth and torques applied to the convecting plasma from the dawn/dusk, $Y$, component of the IMF. Both these models predict similar convection patterns, and indeed, both models play a role in generating the final magnetospheric convection. The reconnection process dominates during periods for which the IMF contains a southward component (in the Earth’s geomagnetic coordinate system), but the viscous process becomes important during intervals of sustained northward IMF. A review of magnetospheric convection is presented in Chapter 2.

1.3.3 Magnetospheric Currents

As magnetic flux is loaded onto the nightside from the dayside, the magnetotail is compressed forcing oppositely directed field lines together. A $\mathbf{v} \times \mathbf{B}$ current is generated at the neutral line between the inward and outward field. This current sheet is known as the cross tail current. The total current carried between $\sim 10 \, R_E$ to $\sim 60 \, R_E$ is typically of the order $10^7 \, A$ (Ofjama and Potemra, 1976). Similarly, a current system flowing across
Figure 1.6 The twin cell convection pattern predicted by the open model of magnetosphere/IMF interaction (co-rotation effects not included). The flow is antisunward across the polar cap (defined as the region of geomagnetic field lines open to the IMF) with return sunward at auroral and subauroral latitudes.
the magnetopause is generated between antiparallel components of the IMF and the
Earth’s magnetic field near the dayside neutral line [see e.g. Lui, 1984].

As the magnetic flux is dragged across the polar cap by the solar wind a $\mathbf{v} \times \mathbf{B}$
voltage is generated across the polar cap, known as the cross polar cap potential ($\phi_{cp}$). A
similar, but opposite voltage is set up in the return flow [e.g. Stern, 1984]. Currents
(known as as field aligned currents, or FACs) set up by these voltages map down field
lines into the highly conductive $E$ region [Sections 1.2.4 and 3.4]. The electrojets are
regions of enhanced $E$ region current at auroral latitudes on the nightside, with the
eastward electrojet approximately west of midnight and the westward electrojet east of
local midnight. The electrojets are Hall currents and are a consequence of the $E \times B$ drift
of the convecting plasma [e.g. Akasofu, 1963; 1984].

The high energy particles trapped in the radiation belts gyrate along magnetic field
lines, and are reflected near the poles by magnetic mirroring as the field intensifies. These
trapped particles are subjected to longitudinal drifts in response to gradients and
curvatures in the geomagnetic field. The direction of these drifts are dependent on the
charge on the particles. Ions move westward and electrons eastward setting up a closed
current system, known as the ring current which is centred on the equator.

1.3.4 Magnetospheric Substorms
Magnetospheric substorms were initially identified by brightening of the auroral arcs [see
Section 1.2.4] and are believed to be the consequence of the storage and release of energy
resulting from dayside and tail reconnection [e.g. Rostoker et al., 1980]. The majority of
substorm signatures appear on the nightside, although the substorm cycle begins with a
southward turning of the IMF at the dayside magnetopause. The nightside substorm
signature is the result of relatively localised episodes of energy transfer from the
magnetosphere into the ionosphere. The energy transfer is characterised by perturbations
in the magnetic field in addition to enhanced auroral activity, with a characteristic time
scale of 2 h to 4 h. The magnetic disturbance is more prominent at higher latitudes,
particularly in the auroral zones where it may result in a magnetic perturbation of the order
of thousands of nT. A substorm is usually divided into three phases; the growth, the
expansion and the recovery.
The growth phase is generally defined as the interval during which magnetic flux is eroded from the dayside by magnetic reconnection and transported to the nightside, loading the magnetotail with magnetic flux and energy. As flux is loaded into the magnetotail the plasma sheet flattens increasing $v \times B$, enhancing the cross tail current and elongating the plasma tail. The erosion of closed flux from the dayside, and the accumulation of open flux in the tail results in a general expansion of the polar cap. Typically the growth phase will last 30 min to 60 min.

The onset of the substorm expansion phase was originally identified by the brightening and poleward expansion of the auroral arc. The substorm expansion phase is associated with the explosive release of energy from the magnetotail, in which the geomagnetic field is believed to become more dipolar. During the expansion phase, instabilities occur in the tail which result in a diversion of the cross tail current down field lines into the $E$ region. This field aligned current (FAC) feeds the westward electrojet before returning to the tail via another FAC to form a current wedge. Colocated with the foot of the western FAC in the auroral ionosphere is an auroral form which distorts and becomes the westward travelling surge. A further consequence of the reconfiguration of the field is the generation of ULF waves with periods between 40 s and 150 s along magnetic field lines. These waves, known as Pi2 pulsations, are transient magnetohydrodynamic signals caused by the sudden change in the magnetospheric field configuration. Other signatures of the substorm expansion phase onset include an earthward surge of plasma (which may be identified by spacecraft or by enhanced ion and electron density measured by coherent radars) and and the ejection of a plasmoid down stream, along the geomagnetic tail (detected by spacecraft).

The recovery phase begins when the bulge of the aurora near midnight ceases to expand poleward; the westward electrojet and the high energy particle precipitation leap poleward. The equatorward boundaries of the auroral oval may also move poleward and the intensities of the westward electrojet and the FAC diminish.

1.3.5 Magnetic Storms
A magnetic storm is a global disturbance on the Earth's magnetic field lasting several tens of hours [see e.g reviews by Akasofu, 1963; Gonzalez et al., 1994]. Dst is a magnetic
index derived from the $H$ component of four low latitude magnetometer observatories, and is designed as a measure of the ring current and is thus an indicator of magnetic storm activity [See Section 3.5.4]. Figure 1.7 presents $Dst$ for a magnetic storm which occurred on 15 to 16 July 1959. The disturbance begins with a rapid enhancement known as a sudden commencement (SC). Since it is followed by an interval of storm activity it is known as a storm sudden commencement (SSC). After the initial enhancement of the SC, there is a decrease in $Dst$ (and hence the $H$ component of the low latitude magnetic field). This is known as the main phase of a magnetic storm. The storm presented is a very large storm with the main phase magnetic perturbation exceeding 400 nT, with the disturbance lasting in excess of 24 h.

The initial phase of a storm is generally believed to be the result of the impact of shocked disturbance in the solar wind upon the magnetopause, compressing the magnetosphere and hence enhancing the $H$ component of the equatorial field. The depression of the $H$ component of the geomagnetic field during the main phase, on the other hand, is the result of an enhancement of the ring current fuelled by the injection of high energy particles during both day and nightside reconnection.

1.4 The Present Investigation

The aim of this thesis is to extend the knowledge and understanding of solar wind/magnetospheric interaction during magnetic storms. The interaction between the solar wind and the magnetosphere can be termed “the magnetospheric transfer function”. This idea is illustrated in Figure 1.8. The input parameters are the solar wind plasma and IMF. The output is the magnetospheric response and may be parametrised by magnetic indices such as $Kp$ and $Dst$, or by individual recordings made by magnetometers or ionospheric radars. These output parameters reflect both the directly driven processes on the dayside and reconnection processes on the nightside.

The magnetospheric transfer function is studied in this thesis employing two principal approaches: statistical and case studies. Statistical studies require large data sets encompassing many events and aim to uncover the principles of operation by averaging out random features to highlight the underlying relations. Statistical studies are limited in the choice of input and output parameters. For example, high resolution IMF and solar
Figure 1.7  The $D_{st}$ magnetic index for the 15-16 July storm [adapted, Akasofu, 1961].

Figure 1.8  Flow chart illustrating the method of approach adopted for this thesis.
wind plasma data (e.g. 15 second averages) are both impractical and unavailable for the study of 30 years of magnetic storms, whereas hourly averages of the IMF and solar wind plasma data are both easily obtainable and manipulable by the available computational resources. Hourly and three hourly global magnetic indices are widely available, spanning many decades. Each index has been constructed to reflect different aspects of geomagnetic activity.

Case studies, on the other hand, allow a detailed, high time resolution investigation (possibly of the order of minutes), encompassing local time responses to changes in the solar wind and IMF at the magnetopause. Individual phenomena, such as substorm occurrences and the nightside convection reversal, can be studied in detail, but underlying relations may not be apparent since an individual event is not necessarily representative of all facets of storms. For a case study a larger selection of input and output parameters are available and usable, such as high resolution IMF and solar wind plasma data, or individual magnetograms and velocity measurements by ionospheric radars.

Statistical methods are employed in this thesis to characterise the solar wind and IMF signatures responsible for magnetic storms. Statistical methods are also utilised to study diurnal (universal time) dependence in both storm onset times and peak in magnetic activity measured by magnetic indices. A case study of a magnetic storm which occurred on 20–21 March 1990 investigates the magnetospheric and ionospheric response to the disturbed solar wind input conditions. For this study, data are examined from 44 individual magnetometer stations, 5 ionospheric radars and 3 digisondes along with high resolution solar wind plasma and IMF data.
CHAPTER 2
Review of Magnetospheric Convection
and Magnetic Storms

2.1 Introduction
A review is presented of recent research in the field of solar-terrestrial physics. It is divided into three sections. The first describes magnetospheric convection stimulated by interactions with the solar wind and IMF, the second section discusses the solar causes of magnetic storms, and the third considers both seasonal and UT variations present in magnetic activity.

2.2 Magnetospheric Convection
The convection flows produced in the polar cap are one of the most important consequences of ionospheric-magnetospheric coupling. They relate directly to the present investigation (see Chapter 4) and the detailed processes involved are now reviewed.

2.2.1 The Open Model Verses the Closed Model and the Cross Polar Cap Potential
As discussed in Chapter 1, two models have been proposed which predict a standard twin cell ionospheric convection pattern with antisunward flow across the polar cap and sunward flow at lower latitudes. These are the closed magnetosphere, or viscous interaction, model [Axford and Hines, 1961] and the open model of the magnetosphere [Dungey, 1961]. The strong dependence of magnetospheric convection on the IMF, in particular the north/south (or Z) component in geocentric solar magnetic (GSM) coordinates [Russell, 1971] indicate that the open model is often dominant. This has been confirmed by statistical studies of the dependence of the cross polar cap potential (measured by polar orbiting spacecraft) on the IMF [Reiff et al. 1981, 1985a; Cowley 1984]. Reiff et al. [1981; 1985a] calculated the empirical relation between the IMF and
the observed cross polar cap potential, $\phi_{pc}$:

$$\phi_{pc}(kV) = 38 + 122G$$  \hspace{1cm} (2.1)

Where

$$G = \frac{\alpha^2 f^2}{1 + \alpha^2 - 2\alpha \cos \theta}$$  \hspace{1cm} (2.2)

$$\alpha = \min\left(\frac{7B_z(nT)}{60}, 1\right)$$  \hspace{1cm} (2.3)

$$f = \max(\alpha - \cos \theta, 0)$$  \hspace{1cm} (2.4)

and

$$\cos \theta = \frac{B_z}{B_i}$$  \hspace{1cm} (2.5)

$B_i$ and $B_z$ are the magnitude and the southward component of the IMF. The empirical relation of Equation 2.1 was obtained from a least squares fit to a theoretical magnetic merging formula [Sonnerup, 1974; Hill, 1975]. Reiff et al. [1985a] also deduced a relation for $\phi_{pc}$ based on the Perreault and Akasofu [1978] epsilon parameter, $\varepsilon$:

$$\phi_{pc}(kV) = 30 + 0.0061\xi$$  \hspace{1cm} (2.6)

where

$$\xi = v_{sw}B_i^2 \sin^4\left(\frac{\theta}{2}\right) = \frac{\mu_0 H_0}{\mu_0^2}$$  \hspace{1cm} (2.7)

and $v_{sw}$ is the solar wind speed, $\mu_0$ is the permeability of free space and $l_0$ is a characteristic scale length of 7 $R_E$. The 38 kV constant in Equation 2.1 and the 30 kV constant in Equation 2.6 suggest that there is always a residual voltage of around 30 kV to 40 kV when the IMF is northward, which has been attributed to the voltage generated by the viscous interaction (although Cowley [1984] suggested that the residual voltage
may be in part be due to the delay of a few hours before the open field lines are closed in
the tail and concluded that the viscous voltage was typically 5 kV to 10 kV). Typically
when the IMF has a southward component the cross polar cap potential, $\phi_{pc}$, is of order
-100 kV, thus during intervals of $B_z$ south, and in general intervals of disturbed magnetic
activity, it is the open model of the magnetosphere which is dominant.

2.2.2 A Fluid Model of Polar Cap Dynamics

During the process of reconnection previously closed magnetic flux is opened, increasing
the size of the polar cap (defined as the region of geomagnetic flux open to the IMF).
Siscoe and Huang [1985] described polar cap expansion in terms of an incompressible
fluid. Since the magnetic energy density of the inner magnetosphere greatly exceeds the
particle energy density the magnetic flux can be treated as an incompressible fluid.
Consequently, recently opened flux that was previously outside the polar cap boundary
(PCB), but adjacent, will flow inside. Stream lines associated with this flow will appear
on the outside wall of the PCB as the outside of the PCB pushes the closed flux away as
it expands. Open flux on the inside surface of the PCB will move outward at the
expansion rate of the PCB resulting in the generation of a simple two cell convection
pattern (Figure 2.1a).

With the exception of the dayside merging gap, there is no flow across the boundary
between the inside and the outside of the PCB. Siscoe and Huang described such a
boundary as "adiaromic" meaning that there was no flow across. Siscoe
and Huang concluded that the temporal behaviour of the polar cap was governed by
Faraday's Law:

$$\phi = \frac{d\phi_{pc}}{dt} = \frac{d}{dt} \left[A_w B_z \right]$$

(2.8)

where $\phi_{pc}$ is the open flux threading the polar cap, $A_{pc}$ is the instantaneous area of the
polar cap, $B_z$ is the magnitude of the polar magnetic field at ionospheric altitudes and $\phi$ is
the voltage across the merging gap boundary. The area of the polar cap increases in the
case of dayside reconnection only, and decreases in the case of tailside reconnection only.
In general, production and loss processes of open flux will occur simultaneously and thus
the size of the polar cap will be determined by a balance between these two processes. In
Figure 2.1 Sketches of ionospheric convection patterns due to magnetic reconnection at the dayside magnetopause and in the geomagnetic tail. The adiabatic polar cap boundary (solid line) expands or contracts depending on the balance between incoming flux on the dayside and outgoing flux in the tail through the dayside and nightside merging gaps respectively (broken lines) for:

a) dayside reconnection only in which the polar cap expands;
b) tailside reconnection only in which the polar cap contracts;
c) flux entering the dayside is twice that on the nightside ($\phi_d = 2\phi_n$); and
d) flux leaving on the nightside is twice that entering on the dayside ($2\phi_n = \phi_d$). The resulting convection pattern is a balance between the convection pattern set up by dayside reconnection and that set up by tail reconnection [from Lockwood et al., 1990].
this model, a flow shear between antisunward flow in the polar cap and sunward flow below the polar cap will occur at the polar cap boundary. In practice, however, convection is also excited by the viscous interaction which will have the effect of moving the observed flow shear to a latitude a few degrees lower than the polar cap boundary [see e.g. Cowley, 1984].

2.2.3 Non Steady State Convection

Lockwood et al. [1990] extended the fluid model of Siscoe and Huang [1985] to discuss the convection pattern resulting from the instantaneous balance between magnetic flux entering the polar cap via the dayside merging gap and the flux lost through the nightside merging gap. In this model all regions of the polar cap and auroral oval are controlled by both day and nightside reconnection. Dayside reconnection will predominantly drive the dayside convection pattern, and similarly the nightside pattern will be primarily influenced by tailside reconnection. These ideas are illustrated in Figure 2.1. When there is only dayside reconnection the polar cap expands as discussed in Section 2.2.2. Here the flow is concentrated on the dayside with a sharp flow reversal near midday. The nightside convection pattern comprises less dense voltage equipotentials with a less well defined flow reversal near midnight. Again the viscous interaction has not been included, thus the flow reversal boundary is also the adiabatic polar cap boundary. There is a net inflow of flux since there is no flux loss in Figure 2.1a and thus the polar cap will expand. The opposite case is illustrated in Figure 2.1b, where there is no dayside merging, but only nightside reconnection. In this situation the convection pattern is similar, but with the emphasis in the opposite sense to Figure 2.1a, with the convection concentrated on the nightside. There is no flux source, and thus the polar cap shrinks as open flux is lost on the nightside. In general the convection pattern will be a balance between these two extremes and Figures 2.1c and 2.1d illustrate the resultant convection patterns. When the dayside voltage, \( \phi_d \), is twice that of the nightside voltage, \( \phi_n \), there is a net overall expansion of the polar cap (Figure 2.1c) with more intense flow on the nightside. When \( \phi_n=2\phi_d \) (Figure 2.1d) there is a net loss of open flux, the polar cap contracts with more intense flow on the nightside.
2.2.4 Observations of Polar Cap Dynamics

Lockwood et al. [1986] considered a more general version of Equation 2.8 for an elliptical polar cap in the form:

\[ \pi a c^2 B_p = \phi_{pc}^t \]  
(2.9)

where \( a \) is the length of the semi-major axis and \( c \) the length the semi-minor axis as illustrated in Figure 2.2 and equating the dayside merging potential to the empirically calculated by Reiff et al. [1981]. Differentiating 2.9 with respect to length gives:

\[ v_{pc} = \frac{ds}{dt} = \frac{1}{2} \left( \frac{\phi_{pc} \cos^2 \theta + c^2 \sin^2 \theta}{B_p \pi t} \right) \]  
(2.10)

Where \( s \) and \( \theta \) are defined in Figure 2.2. For a circular polar cap Equation 2.10 reduces to:

\[ v_{pc} = \frac{ds}{dt} = \frac{1}{2} \left( \frac{\phi_{pc}}{B_p \pi t} \right) \]  
(2.11)

Lockwood et al. went on to demonstrate that the observed equatorward motion of the polar cap identified in a case study from flow shears in the EISCAT radar [Section 3.3.1] during a substorm growth phase propagated equatorward at velocities of the same order of magnitude as those calculated using Equation 2.11, although a factor of 2 greater.

Lester et al. [1990] observed an intrusion of the polar cap into the SABRE radar field-of-view (f-o-v) [Section 3.3.2] during a substorm growth phase in a particularly disturbed interval. In this event, the observed southward propagation of the flow reversal boundary was 400 m s\(^{-1}\), compared with the measured equatorward flow speed of ~100 m s\(^{-1}\), suggesting that the boundary was not adiabatic. However, Lester et al. suggested that this discrepancy may have been due to the radar irregularity drift measurements underestimating the electron drift velocity [Robinson, 1986]. At the time of the substorm expansion phase, Lester and colleagues observed the PCB retreat poleward
Figure 2.2 a) schematic illustration of the twin vortex pattern set up by an elliptical polar cap, illustrating the geometry used to calculate the expansion of the polar cap (from point A) viewed in this example by the EISCAT radar: b) illustration of the origin of the time delay between the time at which the change in the IMF is seen at the spacecraft (in this example AMPTE UKS) and the apparent ionospheric response (seen by EISCAT) [from Lockwood et al., 1986].
at ~1700 m s⁻¹, considerably faster than the equatorward expansion, consistent with the model that the tailside reconnection occurs in explosive bursts.

2.2.5 $B_y$ Effects on Magnetospheric and Ionospheric Convection

Evidence of $B_y$ influence on ionospheric and magnetospheric convection was first observed by Svalgaard [1968] and later Mansurov [1969]. They observed differences in signatures from ground magnetometer data dependent upon whether the Earth was in the toward or away sector of the IMF [Section 1.2.2]. Burch et al. [1985] and a companion paper Reiff et al. [1985b] published empirical models of ionospheric convection for different orientations of $B_y$ and $B_z$ (Figure 2.3). Their studies mapped Birkeland current densities and plasma velocities using hot-plasma phase-space distributions obtained by the High-Altitude Plasma Instrument (HAPI) [Burch et al., 1981]. Their results showed four cell convection patterns for $B_y$ strongly northward (Fig. 2.3a), a three cell pattern when $B_z$ was weakly northward (Fig. 2.3b) and a two cell pattern when $B_y$ was negative and reconnection dominant (Fig. 2.3c). All these models exhibit mirror symmetry between the $B_y$ positive and $B_y$ negative cases. In the case of $B_y$ negative for the northern hemisphere, a strong skew is imposed on the convection pattern by the $B_y$ component of the IMF dragging the antisunward flow toward the morning cell for $B_y$ positive and toward the dusk cell for $B_y$ negative. These latter two convection patterns resemble an “orange and banana” and “banana and orange” respectively. A high latitude radar would observe an eastward movement of the nightside convection reversal in response to $B_y$ turning from positive to negative, whereas a radar near the lower latitudes of the convection pattern might expect to see the nightside reversal move westward for the same change in $B_y$. In the southern hemisphere the convection patterns were observed to be almost a mirror image of Figure 2.3, reflected about the 1100 MLT to 2300 MLT meridian. Many other authors have observed similar asymmetries [e.g. Friis-Christensen et al., 1985; de la Beaujaridere et al., 1986; Burrage, 1988], although the inferred details vary, in particular with the observed patterns for $B_y$ negative not simply being mirror images of the $B_y$ positive patterns.

Another effect of the $B_y$ component of the IMF on magnetospheric convection is to shift the centre of the auroral oval. Holsworth and Meng [1984] measured the
Figure 2.3 Schematic illustration of northern hemisphere ionospheric convection pattern for various orientations of the IMF when: a) $B_y$ positive, convection is primarily excited by the viscous interaction model, with four cell convection pattern in which the inner cell reverse direction between positive and negative $B_y$; b) $B_z$ is weakly northward, a three cell convection pattern is excited with the central cell reversing direction with a change in the sign of $B_y$, and; c) $B_z$ is negative, convection is excited primarily by reconnection and an asymmetric twin cell convection pattern in generated with an “orange and banana” and “banana and orange” configuration for $B_y$ positive and negative respectively [from Burch et al., 1985].
displacement of the centre of the auroral oval as a function of IMF $B_y$ determined by DMSP images. Northern and southern hemispheres are both subject to shifts of $\sim 1^\circ$ of latitude for $\sim 4$ nT change in $B_y$, with the centre of the northern (southern) oval displaced duskward (dawnward) for positive $B_y$. This effect has been observed by many other authors [e.g. Heppner, 1972; Heppner and Maynard, 1987]. Newell et al. [1989], however, pointed out that the dayside cusp precipitation zones are displaced in the opposite sense as the auroral oval as a whole in response to the same $B_y$.

Cowley et al. [1991] described the $B_y$ asymmetries in the convection pattern in terms of the “dipole plus uniform field” model of Lyons [1985]. Figure 2.4 schematically illustrates the resultant field between a northward IMF with a negative $Y$ component and the geomagnetic field. The northern hemisphere is skewed toward the afternoon and the southern hemisphere toward morning. Figure 2.5 presents the resultant equipotential contours across the open northern polar cap calculated by Lyons [1985] for different IMF orientations and magnitudes. In the absence of other forces newly open flux tubes will transport along these equipotentials. The direction of the skew is opposite for $B_y$ of opposing polarity and consistent with the observed convection patterns discussed above.

In addition to the above discussed effects, a newly open flux tube will be subject to a tension (Figure 2.6) as described by Jørgensen et al. [1972]. This stress acts in the same direction to that described by Lyons [1985] and will dominate the initial movement of a newly opened flux tube when the torque will be at its strongest. As the flux tubes gather speed and the $B_y$ tensions reduce the flow moves toward the centre of the polar cap [e.g., Saunders, 1989]. Figure 2.7 illustrates the $B_y$-induced asymmetries. For positive $B_y$ and negative $B_z$ the polar cap boundary is displaced toward dawn. A newly opened flux tube initially moves toward dawn in response to tensions in the magnetic field lines. However, as the flux tube gathers speed the effect the flux tube will move toward dusk as it flows across the centre of the polar cap.

2.2.6 Magnetic Response to IMF and Solar Wind (Linear Filtering)

Many authors have attempted to characterise the magnetospheric response to changes in the solar wind and IMF. Much of this work has employed linear filtering techniques, in which the output function (a selection of magnetic indices [Section 3.5]) is a linear
Figure 2.4 Illustration of the resultant magnetic field between the IMF and geomagnetic field in the YZ (GSE) plane across open polar cap field lines.

Figure 2.5 Resultant equipotential contours across open polar cap field lines for different IMF input conditions [from Lyons, 1985].
Figure 2.6  Schematic illustration, looking down on the north pole of the equatorial cross section illustrating the motion of field lines across the polar cap in response to negative $Y$ component in the IMF. The heavy arrows indicate the direction which plasma flows [from Jorgensen, 1972].

(a) IMF $B_y > 0$

(b) IMF $B_y < 0$

Figure 2.7  Schematic illustration of the resultant $B_y$ asymmetries in the magnetospheric convection pattern due to the three models illustrated in Figures 2.4 to 2.6. See text for details [from Cowley et al., 1991].
combination of past and present values of combinations of solar wind and IMF parameters [e.g. Arnoldy, 1971; Iyemori et al., 1979; Bargatze et al. [1985]. Arnoldy [1971] correlated hourly averages of the $\text{AE}$ index (a measure of substorm activity, see Section 3.5.3) with hourly values of the solar wind and IMF and found the highest correlation occurred when $\text{AE}$ lagged $B_z$ ($B_z < 0$ for $B_z$ negative and $B_z = 0$ for $B_z$ positive) by 1 h.

Bargatze et al. [1985] employed linear filtering techniques on IMF and solar wind data averaged over 2.5 min with $\text{AL}$ (also with a 2.5 min resolution) using $\nu_{\text{ps}}B_z$ as the input function. They constructed 30 filters for different levels of geomagnetic activity using a least squares technique [Weiner, 1949] and employed a year’s worth of data (with data gaps removed by splicing together over undisturbed intervals). Their filters exhibited two characteristic response times of 20 min and 60 min. Bargatze et al. suggested that the 20 min pulse represents the magnetospheric activity directly driven by the solar wind coupling and that the 60 min pulse represents the release of magnetic activity previously stored in the magnetotail associated with the substorm expansion phase. Bargatze and colleagues also concluded that the response of $\text{AL}$ to changes in $\nu_{\text{ps}}B_z$ contained a non-linear component.

2.2.7 Ionospheric Response Times to Changes in the IMF at the Subsolar Magnetopause

Etemadi et al. [1988] and Todd et al. [1988] measured dayside ionospheric response times to changes in $B_z$ at the subsolar magnetopause. In both studies the ionospheric flow data was obtained using the EISCAT Polar experiment and were compared with IMF data from the AMPTE-UKS and -IRM spacecraft, upstream of the Earth’s bow shock. Figure 2.8 presents a summary of the results of both Todd et al. and Etemadi et al. where the ionospheric response time to changes of the IMF from south to north and north to south are plotted as a function of magnetic local time (MLT). A diurnal variability in the ionospheric response is apparent with the shortest response of 5.5 (±3.2) min found in the early to mid afternoon sector and the longest response time of 15.5 (±3.0) min near midmorning and dusk [Todd et al., 1988].

Ruohoniemi et al. [1993] found a response time as short as 2 min at -75° N,
Figure 2.8 Upper panel presents a histogram of the local time coverage of simultaneous ionospheric and IMF data. The bottom panel presents the delay time between changes in sign of the IMF $B_z$ component at the magnetopause and a response measured in the ionospheric convection, plotted as a function of local time [From Todd et al., 1988].
measured by the Goose Bay HF radar [Section 3.3.2], to a northward turning of $B_y$ and is consistent with the shortest dayside response times reported by Etemadi et al. [1988]. Clauer and Friis-Christensen [1988] measured the response time of high latitude (>81°N) ionospheric currents around 0900 MLT to a northward turning of the IMF at the magnetopause to be about 22 min. With comparison to an earlier study by Clauer and Banks [1986] in which a dayside response time of the ionosphere of ~13 min was measured between latitudes 70° N and 80° N following a change in sign of IMF $B_y$, Clauer and Friis-Christensen concluded that the ionospheric response time to changes in the IMF at the magnetopause increases at latitudes greater than 80°N.

Lester et al. [1993], in a case study, considered the local time response of ionospheric convection on the nightside to a southward turning of the IMF. To measure the ionospheric response they employed flow data from four ionospheric radars: Millstone Hill, Sondrestrom, Wick and EISCAT. The results of Lester and co-workers are summarised in Figure 2.9. As for Figure 2.8 the ionospheric response time has been plotted as a function of MLT. Delays of order 5 min to 20 min were measured near dusk and are in agreement with the statistical results of Etemadi et al. [1988] and Todd et al. [1988] at similar local times as discussed above. The nightside response time measured in the Lester et al. study, which was not measured in the previous two studies, was of order 40 min. All these responses occurred during the growth phase of a substorm, with the expansion phase onset occurring ~90 min after the southward turning of the IMF. The results of these three studies suggest a large diurnal variation in the response times of the ionosphere to changes in the polarity of the Z component of the IMF, varying from ~5 min near noon, to ~10 min to 15 min at dusk and dawn, round to ~40 min near midnight.

2.3 The Solar Causes of Geomagnetic Storms

The research outlined in this section is primarily developed in Chapter 5 which is a superposed epoch analysis of magnetic storms, the principle aim of which is to characterise the solar wind and IMF conditions before and during magnetic storms.
Figure 2.9  Response times of the nightside high latitude ionosphere to a southward turning at the magnetopause [adapted, Lester et al. 1993].
2.3.1 The Independence of the Initial and Main Phases of Geomagnetic Storms

It has been known for many years that the size of the sudden commencement (SC) and the intensity of the main phase of a storm are not necessarily related. For example, Piddington [1963] observed that of the 346 SSC events studied by Sugiura and Chapman [1960] the amplitude of the SC was independent of the size of the main phase of the magnetic storm. Piddington [1963] concluded that the size of the main phase of a magnetic storm was independent of the solar wind pressure and density, but possibly dependent on degrees of frictional interaction, and/or dependent on the interplanetary magnetic field strength and direction. Akasofu [1964] independently observed that not all SC events were followed by appreciable main phases. In a study of 7 SSCs, Burlaga and Ogilvie [1969] reported that all seven events were caused by hydrodynamic shocks in the solar wind dynamic pressure, but in addition found five more shocks in the solar wind which were not followed by magnetic storms. Not only do SCs occur without being followed by an appreciable main phase, but Hershberg [1963], in a study of the H component of the magnetic field and the Ap index (a linear version of the Kp index [Section 3.5.1] and a measure of global magnetic activity) concluded that the main phase of a magnetic storm may occur in the absence of a sudden commencement.

Russell et al. [1974], from a study of four geomagnetic storms, demonstrated that the main phase of a magnetic storm was dependent upon the southward component of the IMF, and that a threshold value of IMF $B_z$, dependent on the current level of the ring current, is required to initiate the main phase. Russell and co-workers concluded that a westward solar wind electric field ($-v \times B$) of 1.5 mV m$^{-1}$ was required to maintain $Dst$ at ~-25 nT and a westward electric field of ~2.5 mV m$^{-1}$ to maintain a ring current with $Dst$ ~-60 nT. It is now well established that the main phase of a magnetic storm is strongly related to the southward component of the IMF by the reconnection mechanism described by Dungey [1961] discussed in Section 1.3.2.

A common feature of a geomagnetic storm is the occurrence of substorms. Substorms may result in an enhancement of the ring current, and one possibility is that a geomagnetic storm is simply the result of successive substorm expansion phases onsets which inject particles into the ring current [e.g. Nishida; 1978]. Kamide [1992]
considered whether a substorm occurrence was a necessary condition for a magnetic storm. By consideration of the *Dst* and *AL* index, Kamide concluded that the presence of substorms is not a necessary condition for a magnetic storm, but the condition required for a substorm is also included in the condition for a magnetic storm. For instance a substorm will always occur whenever \( B_z \) is less than \(-3 \) nT averaged over an hour [Kamide, 1977] whereas to cause a large magnetic storm (\( Dst<-100 \) nT) \( B_z \) must be less than \(-10 \) nT for 3 h [Gonzalez and Tsurutani, 1988].

### 2.3.2 High Speed/ Low Speed Stream Interactions

It is now widely accepted that magnetic storms are generally caused by the impact on the magnetosphere of a compression of the upstream IMF and solar wind plasma by high/low speed stream interfaces in the solar wind, or by coronal mass ejections (CMEs). The solar wind is inhomogeneous, with streams of differing velocities flowing from different solar locations. Sharp discontinuities in the velocity and density profiles occur between a high speed rarefied stream and a low speed more dense stream. These interfaces follow the Parker spiral, resulting in high speed streams catching up low speed streams and compressing the IMF immediately upstream. Figure 2.10 presents a superposed epoch plot of 23 abrupt stream interfaces [Gosling et al., 1978]. In addition to a time series plot, Figure 2.10 can be considered as a function of solar longitude, \( \Phi_s \), by the transformation \( \Phi_s = \phi - \lambda \), where \( \phi \), the mean solar angular velocity, is equal to 13.3\(^\circ\)/day and \( t \) is the time difference measured at the Earth in days. There is a sharp increase in proton temperature at the interface (Figure 2.10a), peaking at \( 3 \times 10^5 \) K, a factor of 6 greater than the temperature prior to the interface. Gosling et al. [1978] interpreted these higher temperatures as the result of heating associated with the compression of the gas near the leading edge of the stream. There is a sharp decrease in the plasma density at the interface (Figure 2.10b). This drop in density is discontinuous on a time scale of minutes (by definition for inclusion in the study of Gosling et al.), although the density on both sides of the interface is higher than its long term average of 8.7 \( \text{cm}^{-3} \) [Feldman et al., 1977]. The results of Gosling et al. suggested that the enhancement in density before the discontinuity is centred on the stream interface and is the result of the pressure gradient which accelerates the low speed gas in front of the stream and decelerates the high speed
Figure 2.10 Superposed epoch plots of the solar wind during the spacecraft passage of a high/speed slow/speed stream interaction, with $t=0$ defined at the interface for: a) proton temperature; b) flow angle; c) proton density and; d) flow speed [from Gosling et al., 1978].
gas within the stream itself. In addition the flow angle of the gas at the discontinuity switches from a direction of east of the Sun to one from the west of the Sun (when defining heliospheric north in the positive Z geocentric solar equatorial (GSE) direction; Figure 2.10c). This is a relative motion effect, and in the frame of reference of the rotating Sun there is no deflection. In the corotating frame, the interface will be a shear in the flow, with the flow vectors on each side of the interface directed parallel but with different magnitudes. Finally, Figure 2.10d presents the velocity profile of the superposed epoch analysis of Gosling et al. [1978]. The velocity has a positive gradient prior to the discontinuity, the result of the pressure gradient accelerating the slow moving gas near the interface. The peak in velocity occurs several hours after the discontinuity, again the result of the pressure gradient which decelerates the gas within the high speed stream.

2.3.3 Coronal Mass Ejections (CMEs)

Coronal mass ejections (CMEs) are usually associated with eruptive solar prominences, and occupy substantial volumes of the solar corona [e.g. Hundhausen et al., 1984]. These ejecta may disconnect magnetically from the Sun to form closed loops, or bubbles. Figure 2.11 presents a time series plot of a typical CME [Lindsay et al., 1994]. Since, in the example shown, the CME is travelling at a higher velocity than both the ambient solar wind and the Alfvén velocity a shock wave is generated in front of the cloud, which accelerates and compresses the gas upstream of the CME resulting in enhanced velocity, density and temperature (the latter the result of kinetic energy transferred into thermal energy [Colburn and Sonnet 1966]). The passage of the body of the CME (e.g. at 1 AU) is characterised by the decrease of the ion temperature below ambient and an enhancement in the dynamic pressure [e.g. Burlaga, 1991, Lindsay et al., 1994].

Gosling and McComas [1987] suggested that in addition to straightforward compression of the IMF by a CME, strong out-of-the-ecliptic field components may be generated by a draping of the IMF about a CME in addition to compressing the field. Figure 2.12 illustrates the effect, with the centre of the plasmoid lying within the ecliptic plane. Flow accelerations and deflections of the ambient plasma out of the ecliptic result in draping about the plasmoid. The magnetic field, which is primarily in the X direction
Figure 2.11 A typical example of a coronal mass ejection showing an initial enhancement in ion velocity, density, temperature and dynamic pressure during the passage of the shock with the ion density, temperature and pressure falling at the passage of the leading edge of the CME [from Lindsay et al., 1994].
Figure 2.12 Illustration of the field draping about a coronal mass ejection producing strong out of the ecliptic magnetic field by rotation of the $X$ component of the IMF [from Gosling and McComas, 1987].
becomes reorientated such that a large component resides in the Z direction. This field is then further enhanced in magnitude by shock compression. Gosling and McComas further suggested that the strong southward components generated by this mechanism may be an important factor in generating geomagnetic activity. Recently, Phillips et al. [1993] concluded that the geomagnetic effectiveness of a CME and post shock solar wind is ordered by the speed and by the southward component of the IMF, with the larger storms associated with the higher solar wind velocities.

2.3.4 On the Origin of Geomagnetic Storms

Tsurutani et al. [1988] studied the origins of the strong southward components of the IMF responsible for the ten largest storms detected during a five hundred day study. Nine of the 10 storms were the result of high magnetic fields associated with the stream-stream and CME interactions described above. Gosling et al. [1990] reported that 25 of the 34 events studied in the interval 1978 to 1982 were associated with the transient disturbance in the solar wind caused by a CME. Gosling et al. concluded that slow moving CMEs are relatively geomagnetically ineffective because they do not interact strongly with the ambient solar wind ahead, whereas such interactions for fast CMEs lead to substantial compression of both the ambient plasma and the leading portion of the CME itself. Such a speed difference is also essential for producing draping of the ambient IMF about the CME and to compress the field. In a later study with an expanded data set, Gosling et al. [1991] found that 36 of the 37 largest storms are associated with the Earth passage of shock disturbances or CME. Gosling and co-workers concluded that shock disturbances and CMEs were increasingly the cause of geomagnetic storms for increasing storm magnitudes.

Tsurutani et al. [1992] studied the five largest storms between 1971 and 1986, characterised by the Dst index, to determine their solar and interplanetary causes. Tsurutani et al. concluded that all five events were associated with exceptionally high values of $B_z$ (the southward component of the IMF), although not all events were associated with enhanced solar wind velocities. They also concluded that long duration precursor southward magnetic fields which exist for days prior to the passage of the shock are important in the generation of large magnetic storms. Such precursor fields
2.4 Seasonal and UT variations in Geomagnetic activity

The seasonal and UT variations in geomagnetic activity are now reviewed as these are relevant to the statistical storm study presented in Chapter 6.

2.4.1 Semi-Annual Variations in Geomagnetic Activity: The Heliospheric Latitude Model

The existence of a semi-annual variation in geomagnetic activity had long been established when Cortie [1912] utilised 23 years of magnetic indices for a single observatory to study the seasonal variation of geomagnetic activity. Peaks in activity were noted in late February and late August and Cortie suggested that this semi-annual activity was the result of heliospheric latitude effects. The Sun's equator is inclined to the ecliptic plane by 7.2°. As the Earth rotates around the Sun it will reach its maximum heliospheric latitudes on 5 March and 6 September, in near agreement with Cortie's results. Since, on average over a solar cycle, sunspots are more frequent at solar latitudes greater than 7°, and that sunspots were linked to magnetic activity, Cortie argued that it is more likely that the Earth will lie in the path of particle streams ejected from, or near, sunspots when the Earth is at higher heliospheric latitudes.

2.4.2 Semi-Annual Variations in Geomagnetic Activity: The McIntosh Effect

By mean of the planetary indices of magnetic disturbance over a 59 year period, Bartels [1932] established magnetic activity peaks near the two equinoxes. He also concluded that there was no evidence of enhancement in March (September) during years of predominant sunspot activity in the northern (southern) hemisphere of the Sun. McIntosh [1959], in a study employing the K index and the related planetary index Kp [Bartels, 1949; Section 3.5.1] found a summer maximum and winter minimum and a semi-annual component with equinoctial maxima. McIntosh also found that the annual component increased with increasing latitude, whereas the semiannual component was relatively independent of latitude. McIntosh concluded that the "semi-annual component
arises because of a systematic annual variation of the angle between the Earth's (dipole) axis and the Sun-Earth line ($\psi$), along which travel the particles which cause the magnetic disturbance. He suggested that the annual variation "is probably caused by an atmospheric dynamo effect" and that "asymmetry about the equator of ionospheric wind circulation appears a likely result of the 6% additional heat radiation received by the Earth at perihelion (early January) relative to aphelion (early July)". In this model, geomagnetic activity is modulated by $\sin^2\psi$, with the optimum condition for energy transfer from the solar wind to the magnetosphere when $\psi$ is closest to 90°. This model is now known as the "McIntosh effect". Boller and Stolov [1970] suggested that the semiannual variation is the result of "Kelvin-Helmholtz instabilities, generated at the magnetopause, which initiate the modulation of geomagnetic disturbances".

Crooker and Siscoe [1986] employed computer models of superposed fields to demonstrate that when the model IMF exceeds a critical value, the field configuration in the Chapman-Ferraro current plane [Chapman and Ferraro, 1931] ceases to expose closed field lines to the solar wind, resulting in a saturation of the reconnection energy coupling mechanism. The critical value depends upon the IMF orientation, stagnation pressure and the Earth's magnetic dipole tilt toward the solar wind. When $\psi$, the angle between the Earth's dipole axis and the Earth-Sun line is smallest, reconnection would be inhibited as a result of the tendency for open tail lobe field lines to drape over the closed dayside field. Crooker and Siscoe suggested that this would result in a maximum coupling efficiency between the geomagnetic field and the IMF at the equinoxes when $\psi$ is closest to 90° and minimum efficiency at the solstice when $\psi$ is smallest. This would produce a seasonal variation which was in phase with the observed activity.

2.4.3 Semi-Annual Variations in Geomagnetic Activity: The Russell McPherron Effect

Russell and McPherron [1973] offered a different explanation of the semiannual variation. They proposed that it was caused by "a semiannual variation in the effective southward component of the interplanetary field" and that "the southward field arises because the interplanetary field is ordered in the solar equatorial coordinate system, whereas the interaction with the magnetosphere is controlled by a magnetic coordinate system". This
is illustrated in Figure 2.13. Part of the dawn-dusk, or $Y$, component of the IMF in geocentric solar equatorial (GSE) coordinates [see e.g Russell, 1971, for a description of the coordinate systems] resulting from the Parker spiral is projected into the north-south, or $Z$, component in geocentric solar magnetic (GSM) coordinates. This transformation would produce maximum $B_Z$ (GSM) when the magnetic dipole is at its most inclined to the $Y$ (GSE) direction at the equinoxes. Berthelier [1976] sorted magnetic indices by the dominant polarity of the IMF $Y$ component. Her results showed an annual variation in geomagnetic activity with a spring peak for negative $B_Y$ and an autumn peak for positive $B_Y$, consistent with the Russell and McPherron effect.

2.4.4 Semi-Annual Variation of Large Geomagnetic Storms

A semi-annual variation in large magnetic storms has also been observed. The histogram of Figure 2.14a [Jones, 1955] represents the number of events for which the $H$ or $Z$ components exceeded 300 nT or the $D$ component exceeded 60° recorded at the Greenwich or Abinger magnetometer stations for data recorded between 1874 and 1954. A pronounced seasonal variation is observed, with more than twice the number of events recorded at the equinoctial months compared with solstitial months. Figures 2.14b and c present the results of Crooker et al. [1992] illustrating the semi-annual variation of events with $Ap \geq 100$ nT from 1932 to 1989 (Figure 2.14b) and events with $Dst \leq -250$ nT from 1932 to 1990 (using $Ap>160$ nT as a proxy for $Dst$ prior to 1957; Figure 2.14c). Both these histograms have peaks near the equinoxes, similar to the study of Jones (Figure 2.14a). Crooker et al. described these variations in terms of the Russell and McPherron effect on the enhanced $Y$ (GSE) component fields resulting from compression of the IMF draped about a CME (Figure 2.15). Crooker et al. concluded that the fields arising from post shock flow of CMEs during reconnection may be responsible for more pronounced semi-annual variation of large geomagnetic storms. They also concluded that they may also serve as priming of the Earth’s ring current, thus favouring the generation of large geomagnetic storms.
Figure 2.13 Illustration of the Russell and McPherron effect in which the $Y$ (GSE) component of the IMF is projected into the $Z$ (GSM) direction of the geomagnetic field [from Crooker et al., 1992].
Figure 2.14 The semi-annual variation of "great" magnetic storms with: a) $D>60'$ or $H>300$ nT at Greenwich or Abinger ground magnetometer stations [Jones, 1955]; b) with $Ap\geq100$ nT, and c) with $Dst\leq-250$ nT [Tsurutani et al., 1992] with $Ap>160$ nT used as a proxy for $Dst$ prior to 1957 [from Crooker et al., 1992].
Figure 2.15 Illustration of field draping about a CME in the $XY$ (GSE) plane, in which the $Y$ (GSE) component resulting from the Parker spiral is enhanced. This enhanced $Y$ (GSE) component is then projected into the $Z$ (GSM) direction resulting in large $B_z$ negative components and hence leading to large geomagnetic storms [from Crooker et al., 1992].

Figure 2.16 Averaged UT variation of the K index at 12 observatories for days with $Kp$ sum greater than 20 from 1950 to 1955 illustrating the UT variation in geomagnetic activity for a) June; b) December and c) June minus December [from McIntosh, 1959].
2.4.5 Season-Dependent UT Variations in Geomagnetic Activity

In addition to the seasonal variation in geomagnetic activity discussed above, a universal time (UT) component has also been observed. Studies of UT variations have been undertaken using many different magnetic indices. When studying UT variations in geomagnetic activity, it is important to distinguish between global activity and local time variations, and potential local time bias in the data must be taken into account. McIntosh [1959] studied the daily variations of the $K$ index from twelve observatories. McIntosh subtracted an averaged daily activity in December from the averaged June variation to cancel out any season dependent variations, or biases, and enhance any season independent activity. Figure 2.16 presents his results for the sum of the $K$ index, at 12 observatories for (a) June, (b) December and (c) 'June minus December'. UT varying activity is observed in both June and December's activity, with differing phases. 'June minus December' shows a more pronounced and symmetric variation with a peak between 0600 UT and 0900 UT and a trough between 1500 UT and 1800 UT. Again McIntosh attributed this activity to changes in $\psi$ [Section 2.4.2]. Boller and Sto lov [1970] encompassed the diurnal UT activity in their model which described the seasonal variation of magnetic activity in terms of a UT variation in Kelvin-Helmholtz instabilities [Section 2.4.2]. Although this model does not predict the amplitudes of the magnetic response, it does predict that the growth phase of the instabilities is proportional to $\sin^2 \psi$.

Figure 2.17 presents the UT variation of $\sin^2 \psi$ as a function of month. The most pronounced UT variations are predicted during solstice months with peaks in activity at 0439 UT near the winter solstice and 1639 UT near the summer solstice. The smallest peak to peak amplitudes are predicted at the equinoxes, which are "double humped".

The magnetic index $Am$ is derived from 15 northern hemisphere and 11 southern hemisphere subauroral stations which are divided into 8 groups distributed approximately evenly in longitude and was developed specifically to study UT variations of magnetic activity [Mayaud, 1967; Section 3.5.2]. Mayaud [1967] subtracted winter from summer months, in a similar fashion to McIntosh [1959], for UT activity measured using the $Am$ index. The top panel of Figure 2.18 [Russell, 1989] presents the UT variation of the mean $Am$ index for the four equinoctial months. With the exception of the high average in the 2100 UT to 2400 UT bin, observed by both Mayaud [1980] and Russell [1989], there...
Figure 2.17 The variation of $\sin^2 \psi$ as a function of UT, illustrating the UT variation predicted by the McIntosh effect for months: a) January; b) February; c) March; d) April; e) May; f) June.
Figure 2.18 UT variation of the $Am$ index measured at a) the Equinoctial months and b) summer months minus winter months [from Russell, 1989].
is no UT variation. Russell [1989] argued that a double humped peak would be expected at the equinox from the McIntosh effect since the peaks at both the equinoxes predicted by the McIntosh model are in phase, and that the absence of such peaks suggested that the McIntosh effect does not play an important role in the generation of UT activity. He also argued that the “summer minus winter” variation in the Am index, presented in Figure 2.18b, is not consistent with the McIntosh effect since the peak activity occurs at 0623 UT (0524±9 UT in his revised analysis using a larger data set [Russell, 1990]), calculated from a Fourier analysis of the UT variation whereas the McIntosh effect predicts a peak at 0439 UT. Russell argued that it was appropriate to assume no energy storage time because energy coupling is thought to occur directly into the ionosphere via waves or field aligned currents generated in Kelvin-Helmholtz instabilities, and thus the observed peak was inconsistent with the McIntosh effect. Berthelier [1990], however, claimed that the observed UT variation was not inconsistent with the McIntosh effect with Russell’s revised delay of 45 min, particularly as Am is a 3 h index.

In a letter, Scurry and Russell [1990] reported that the seasonal variation in Am was only visible in data when the IMF was negative. Thus Scurry and Russell concluded that the UT activity observed in the Am index could not be a result of Kelvin-Helmholtz instabilities as described by Bolter and Stolov [1970], but suggested that the instabilities may enhance the reconnection process (e.g. by the patchy reconnection model proposed by la Belle-Hamer et al. [1988]) since the observed phase lag of 45 min is in agreement with the expected time delays resulting from tail side storage of dayside reconnected flux [Bargatze et al., 1985; Section 2.2.6].

Other mechanisms have been suggested which would generate UT variations in the observed magnetic activity. The model described in Section 2.4.2 by Crooker and Siscoe [1986] also predicts a UT variation in the efficiency of energy coupling. In their model reconnection is most efficient when $\psi$ is nearest 90° and is thus in phase with the McIntosh effect. Kivelson and Hughes [1990] suggested that the conditions for tailside reconnection are most favourable when the tail is subject to the most stress. This they argued would occur when the geomagnetic dipole axis is at its most inclined to the Earth-Sun line and minimum when the dipole axis is directed in the dawn/dusk plane. Kivelson and Hughes argued that tail bending is absent when the dipole is situated toward the dawn
or dusk, and that since “tail stress must reach a relatively high level before a substorm
discharge the stored energy” that “when the substorm finally occurs, it is a big one and
the 3 h index is large”. When the tail is less bent, more energy can be stored resulting in
larger substorm expansion phase onsets and hence large change in difference magnetic
indices such as \( \Delta m \), whereas when the tail is stressed, a succession of more rapid smaller
substorms will occur resulting in smaller changes to the magnetic field and therefore
lower values of \( \Delta m \). The resultant magnetic activity would be in phase with the McIntosh
effect.

2.4.6 Season-Independent UT Variations in Geomagnetic Activity
Recently, Saroso et al. [1992] employed the \( Ap \) and \( Dst \) indices to demonstrate a season
independent UT variation in magnetic activity. Figure 2.19a is a histogram of the number
of data points of \( Ap > 80 \) nT. The minimum occurrence is in the 0900 UT to 1200 UT
bin, which is inconsistent with the minimum observed in the number of \( Dst \) occurrences
less than \(-80 \) nT (Figure 2.19b), where the minimum occurs in the 1200 UT to 1500 UT
bin. Saroso and colleges then calculated the rate of change of \( Dst \) (\( dDst/dt \)) (Figure 2.19c)
and observed that it was in phase with the UT variation of \( Ap \) (Figure 2.19a). Saroso an
coworkers suggested that the UT activity may be the result of longitudinal asymmetries
in the geomagnetic field distribution. They calculated the UT variations of the nightside
auroral oval magnetic flux employing a model based on the IGRF. Saroso et al. found
that the oval magnetic flux peaks at around 1030 UT, anti-correlated with the observed
variation in \( Ap \) and \( dDst/dt \). Saroso and co-workers suggested that as the magnetic field
in the plasma sheet increases, the plasma drift velocity will decrease assuming the electric
field remains constant since \( v_B = \frac{E}{B} \) thus reducing the plasma flow from the
magnetotail.

2.5 Summary
The morphology and physical mechanisms of magnetic storms and substorms have been
reviewed. In particular the ionospheric convection flow has been described, together with
magnetospheric and solar wind interactions which govern the flow pattern. The
Figure 2.19 UT variation of the number of a) $Ap$ values greater than 80 nT; b) $Dst$ $<-80$ nT and c) $dDst/dt$ $<-8$ nT s$^{-1}$ for years 1957 to 1984 [from Saroso et al., 1993].
characteristic features of storms and substorms have been reviewed and related to their production mechanisms. An understanding of these features of the solar terrestrial interaction processes is necessary in order to understand the studies reported in this thesis. In later chapters both the individual response times and the more general features such as seasonal and UT dependencies will be addressed.
CHAPTER 3

Instrumentation

3.1 Introduction

This chapter gives a brief résumé of the instrumentation from which data are presented in later chapters. There are four principal types of data employed in this thesis: spacecraft (solar wind and IMF parameters), ionospheric radar (ionospheric convection), ground magnetometer (measurements of the Earth’s magnetic field) and magnetic indices (magnetic parameters derived from a selection of ground magnetometer stations).

3.2 Spacecraft

Since the launch of IMP-1 in 1963, spacecraft have been monitoring the solar wind plasma and interplanetary magnetic field (IMF). These spacecraft include AIMP-1 and 2, IMP-3 to 8, HEOS-1/-2, VELA-2 to 6 and ISEE-1 to 3. For the types of study undertaken in this thesis, the optimum position of the spacecraft recording the IMF and solar wind plasma data is on the Sun-Earth line fairly close to the bow shock, otherwise the spacecraft is recording data from a region of the solar wind which may be different to that which impacts upon the magnetosphere. With the exception of ISEE-3, all spacecraft were in orbit about the Earth and thus near this optimum position for only a small percentage of the time. ISEE-3 was in a halo orbit near the Lagrangian gravitational neutral point, but suffers from the disadvantage that it was 260 $R_E$ upstream of the Earth, and it is thus uncertain as to whether the measured plasma would strike the Earth’s magnetosphere. Hourly averages of solar wind and IMF data are widely available from World Data Centres (WDCs), and incorporate all available data for the intervals which the spacecraft were upstream of the bow shock. In total, solar wind plasma and IMF data are available for approximately 50% of the interval 1963 to 1991. For the case study presented in Chapter 4, 15 s IMF and 60 s to 300 s resolution solar wind plasma data from the IMP-8 spacecraft, which was in an equatorial orbit at a radius of $-30 R_E$, are
3.3 Ionospheric Flow Measurements

Three types of instrumentation provide the estimates of the ionospheric flow measurements reported in this thesis: coherent and incoherent scatter radars and ionosondes (digisondes).

3.3.1 Incoherent Scatter Radars

For transmitted wavelengths greater than the Debye length, $\lambda_D$, incident radiation is incoherently scattered off ion and electron acoustic waves in the ionospheric plasma. These acoustic modes are generated by random thermal motion. In the ionosphere $\lambda_D$ depends on latitude, height, local time and on the solar cycle. Although termed incoherent scatter, this mechanism is not true incoherent Thompson scatter. The scattered power is contained in a narrower bandwidth than for Thompson scatter and therefore the returned signal will have a higher signal per unit bandwidth (and a higher signal to noise ratio). The incoherent scatter spectrum comprises a double peaked form, the shape of which contains information about electron density, electron and ion temperatures, and ion mass. In this thesis measurements of the ion velocity only are considered which are calculated from the Doppler shift of the returned spectrum.

Incoherent scatter radars utilised in this study include the European Incoherent SCATter radar (EISCAT) [Rishbeth and Williams, 1985], Millstone Hill (MH) [Foster et al., 1985] and Sondrestrom [Kelly, 1983]. Figure 3.1 presents polar maps of the ground instrumentation, employed in the case study undertaken in Chapter 4, in both geographic coordinates (Figure 3.1a) which includes coast lines and geomagnetic coordinates based on the IGRF at epoch 1990.25 and at sea level (Figure 3.1b). The field-of-views (f-o-vs) of the incoherent radars are coloured blue. The EISCAT radar consists of a tristatic UHF (933.5 MHz) incoherent radar with transmitter and receiver at Tromsø (Norway) and receivers only at Sodankylä (Finland) and Kiruna (Sweden), together with a VHF (224 MHz) monostatic system at Tromsø. For the study undertaken in Chapter 4 the UHF system of the EISCAT radar was operational from 15 UT on March 20, running Common Program 2 (CP-2). In this mode the radar has four pointing positions with a 6
Figure 3.1 Map illustrating the a) the geographic location and b) the IGRF magnetic location of instruments employed in this thesis. The yellow areas represent the field-of-view of coherent radars (Wick and Goose Bay) and the blue the field-of-view of incoherent radars (EISCAT, Millstone Hill and Sondrestrom). Digisondes are coded green (Qaanaaq, Goose Bay and Millstone Hill) and ground magnetometer stations are coded red comprising USGS(△), SAMNET (▼), EISCAT Magnetometer Cross (▲), BGS (○) and Russian (★).
minute cycle time. The geomagnetic positions of the intersection heights at 268 km altitude for each pointing position are: 66.2° N, 103.6° E (vertical), 65.8° N, 103.1° E (south), 65.1° N, 104.8° E (east) and 66.0° N, 103.2° E (field parallel). The Millstone Hill (MH) radar is a monostatic incoherent scatter radar with an operating frequency of 440 MHz located at Westford, Massachusetts. During the interval studied in Chapter 4 the MH radar operated a beam swinging mode [see Section 3.3.4] with a cycle time of 38 min on March 20 and 42 min on March 21. The radar f-o-v covered magnetic latitudes 53° N to 71° N with an elevation angle of 6° and the azimuthal angle viewed from due north (azimuth = 0°) anticlockwise through to the west (azimuth = 260°). The data were then processed by merging pairs of line-of-sight (l-o-s) velocities using the procedure of Holt et al. [1984] to obtain vector ion drift velocities. The Sondrestrom radar is a monostatic radar situated on the west coast of Greenland, near Sondre Stromfjord with an operating frequency of 1300 MHz. The operating mode of the Sondrestrom radar during the interval studied in Chapter 4 alternated between multiple position mode (beam swings) and elevation scans in the magnetic meridian. The ionospheric convection was determined with the multiple position mode and covered magnetic latitudes 62° N to 82° N. l-o-s ion velocities from position pairs were used to generate vector ion velocities.

3.3.2 Coherent Scatter Radars

Coherent radars scatter radio signals off field aligned irregularities of enhanced electron density. Coherent backscatter will be detected if the radar k-vector is perpendicular to the field aligned irregularities. At auroral latitudes the field is nearly vertical, therefore the radars need to be at relatively low elevation angles to comply with the orthogonality requirement. Radars scattering off E region irregularities use VHF and UHF radio signals (Figure 3.2a). For receiving backscatter from F region irregularities, VHF and UHF radars are generally unable to meet the orthogonality requirement, and HF radars must be used, as the radar beam may be refracted into the required direction (Figure 3.2b).

The irregularity scattering cross section of coherent backscatter is considerably greater than that of incoherent scatter. In addition coherent radars will illuminate a larger volume of the ionosphere, thus giving larger spatial coverage. Coherent radars, however,
Figure 3.2 The geometry of a) VHF and UHF and b) HF scattering from field aligned irregularities. The ionospheric bending of HF waves allows the reception of an F-region backscatter.
suffer from the disadvantages that they can only measure backscatter intensity and the phase speed of the irregularity drift and that the presence of field aligned irregularities in the auroral ionosphere is required before backscatter will occur. There are two principal types of field-aligned irregularities from which backscatter will occur. Gradient drift irregularities dominate in the $F$ region, and two stream instabilities dominate in the $E$ region [e.g., Fejer and Kelly, 1980]. The measured Doppler velocity from two stream instabilities is limited by the sound speed in the plasma [Nielsen and Schlegel, 1983, 1985; Robinson, 1986], thus the measured 1-o-s velocity may only provide a lower limit of the true 1-o-s drift velocity. In practice, coherent scatter radars consist of phased arrays of antennas, in which several beams are generated in azimuth at angles at which constructive interference occurs. In contrast, incoherent scatter radars usually generate a single beam from a single parabolic dish.

Data from two coherent radars are considered in this thesis: SABRE [Nielsen et al., 1983] and Goose Bay [Greenwald et al. 1985]. SABRE (Sweden And Britain Radar-auroral Experiment) is a VHF coherent radar with a 20 s sampling interval and a f-o-v covering geomagnetic co-ordinates 84°E to 96°E and 59°N to 66°N (Figure 3.1, yellow colour). Since SABRE is an $E$ region radar, scattering primarily off two-stream instability irregularities it is limited by the sound speed in the plasma as discussed above. From its deployment in 1981 up until 1986 SABRE was bistatic, with stations at Wick in Scotland and Uppsala in Sweden. Since October 1986, SABRE has been a monostatic radar with only the Wick radar operational, and such single station data is employed in this thesis. The Goose Bay (GB) radar is a monostatic HF coherent radar situated in Labrador with a f-o-v covering magnetic coordinates $66^\circ$N to $84^\circ$N and $-5^\circ$E to $60^\circ$E (Figure 3.1) and operates with a 96 s scan. During the interval investigated in Chapter 4 the Goose Bay monostatic HF coherent radar was operating in a “beam-swinging” mode to obtain vector flow measurements from the line of sight velocities [Ruohoniemi et al., 1989].

3.3.3 Digital Ionosondes (Digisondes)

Ionosondes measure ionospheric structure by measuring the reflected signal from a frequency swept radio transmission. The digital ionospheric sounding system Digisonde 128PS, in addition to operating in a standard ionogram mode (with full range
operates in a “Doppler-Drift” mode, with a limited number of frequency-range bins, but full resolution in Doppler and incident angle [Bihl and Reinisch, 1978] and again generate vector flow components using digital beamforming techniques. The measured Doppler velocity of the ionospheric reflection point can be employed as a proxy for the bulk motion of the ionosphere. Doppler measurements from three digisondes are used in this thesis (Figure 3.1): Goose Bay (GB; 62.0°N, 23.3°E; geomagnetic), Qaanaaq (85.7°N, 34.4°E; geomagnetic) and Millstone Hill (MH; 53.8°N, 23.3°E; geomagnetic). In general during the interval under study, the digisondes have temporal resolutions of 30 min, 15 min and 5 min for GB, Qaanaq and MH respectively.

3.3.4 Beamswinging

"Beamswinging" is a general term for techniques whereby vector components are deduced from line-of-sight velocity measurements from, for example, an ionospheric radar. The basic principle is to measure the line-of-sight ionospheric flow along two directions which are preferably orthogonal. The scan may be done by temporal and/or spatial variation of the beam. Assumptions as to how the ionospheric flow (and electric field) vary between the two points (which may be measured by temporal or spatial changes) are then made, often assuming that the flow in each of the two beams is the same. One method (employed in this thesis) measures points chosen to lie along along an L-shell, where it is assumed that the ionospheric flow will vary only with L-shell [e.g. Ruohoniemi et al., 1989]. Beamswinging techniques can, however, deduce inaccurate flow velocities at times of flow shears or gradients in the radar field-of-view [e.g. Freeman et al., 1991; Yeoman et al., 1992].

3.4 Ground Magnetometer Measurements

Measurements of the Earth’s magnetic field have been undertaken for several centuries. In the last 20 to 30 years several digital recording chains of magnetometers stations have been set up by different institutions and countries. Table 3.1 presents the geographic and geomagnetic coordinates (based on the IGRF with epoch 1990.25 and altitude 0 m) and L shell of each of the stations from which data is employed in this thesis. In addition the
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**Table 3.1** Table presenting the geographic and geomagnetic (IGRF) locations and L shells for the 44 ground magnetometer stations from which data is employed in this thesis.
position of the magnetometer stations are presented in red in Figure 3.1. The United States Geological Survey (USGS) magnetometer chain consists of 13 fluxgate magnetometer stations situated in the USA (Figure 3.1, squares). The USGS magnetometer data may be recorded with either 1 s or 5 s integration times [Herzog, 1992]. The British Geological Survey (BGS) magnetometer chain comprises 3 fluxgate magnetometer stations in the United Kingdom at Lerwick, Eskdalemuir and Hartland (Figure 3.1, circles), with data sampled every 10 s [Clark et al., 1990]. In Chapter 4, 60 s averages of BGS and USGS data are employed. The UK Sub-Auroral Magnetometer Network (SAMNET) magnetometer chain consists of seven magnetometer stations in the UK and Scandinavia (Figure 3.1, triangles-apex down) with a 5 s temporal resolution [Yeoman et al., 1990b]. The EISCAT Magnetometer Cross consists of seven magnetometer stations in northern Scandinavia (Figure 3.1, triangles-apex up) with a 20 s integration time [Lühr et al., 1984] and is a cooperative project funded by German and Scandinavian research groups. In addition, analogue plots from 14 Russian magnetometer stations are available (Figure 3.1, crosses), of which 7 have been digitised at a temporal resolution of 60 s by D. Knipp and B. Emery. The digitised stations are: MGD, YAK, DIK, POD, NVS, SVD and BOX. In this thesis the coordinate system adopted for ground magnetometer measurements is the \( H \), \( D \) and \( Z \) system. The \( H \) component is directed toward geomagnetic north, with the \( D \) component perpendicular toward magnetic east and the \( Z \) component vertically downward.

The spatial resolution of ground magnetometers is governed by the height of the \( E \) region, and is \( \sim 100 \) km. Individual magnetometer stations give little information regarding ionospheric and magnetospheric currents, whereas a chain of mid-latitude stations may reveal the location of the substorm current wedge [Lester et al., 1983, 1984]. To calculate the \( E \) region electric field, and hence \( E \) region current, the conductivity of the medium must be known. The current density is given by

\[
\mathbf{j} = \sigma_0 \mathbf{E}_0 + \sigma_p \mathbf{E}_p + \sigma_{0p} \frac{\mathbf{E}_0 \times \mathbf{B}}{\mathbf{B}}
\]

(3.1)

where \( \mathbf{E} \) and \( \mathbf{B} \) are the ionospheric electric and magnetic fields and \( \sigma_0, \sigma_p, \sigma_{0p} \) are the
parallel, Pedersen and Hall conductivities respectively:

$$\sigma_p = \frac{e^2 n_i}{m_i (v_{in} + v_{in}^e)} + \sum_i \frac{e^2 n_i}{m_i v_{in}^i}$$  \hspace{1cm} (3.2)

$$\sigma_e = \sum_i \frac{en_i}{B} \left( \frac{v_{en} \Omega_{ei}^2}{\Omega_{ei}^2 + v_{en}^2} + \frac{v_{en} \Omega_{ei}^2}{\Omega_{ei}^2 + v_{en}^2} \right)$$  \hspace{1cm} (3.3)

$$\sigma_H = \sum_i \frac{en_i}{B} \left( \frac{\Omega_{ei}^2}{\Omega_{ei}^2 + v_{en}^i} - \frac{\Omega_{ei}^2}{\Omega_{ei}^2 + v_{en}^i} \right)$$  \hspace{1cm} (3.4)

where $\Omega_{ei}$ and $\Omega_{ee}$ are the ion and electron gyro frequencies, $v_{in}$ and $v_{en}$ are the ion and electron collision frequencies with neutrals, $n_i$ is the ion number density per species of ion $i$, and $e$ is the charge on an electron [Rees, 1989]. Equations 3.2 to 3.4 demonstrate that the $E$ region conductivity and hence ionospheric current density [Equation 3.1] has a complex dependence on ion and electron gyro-frequencies and collision frequencies. In general, $E$ region conductivities increase in the auroral oval, resulting in larger magnetic perturbations in the measured ground magnetic field. Figure 3.3 presents a typical mid-latitude height profile of parallel, Hall and Pederson conductivities. In the $E$ region the Hall conductivities dominate, with the ratio reaching parity at ~130 km, entering the $F$ region, whereupon both conductivities fall off sharply with increasing altitude. At higher altitudes where collisions are negligible it is the parallel conductivity which dominates.

Powerful computer modelling programmes such as AMIE [Richmond and Kamide, 1988] require assumptions to calculate the conductivity, but are able to deduce gross characteristics of the ionospheric convection pattern from a large array of magnetometers alone. In this thesis, however, the ionospheric flow is primarily deduced from ionospheric radar measurements.
Figure 3.3 Typical conductivity profiles of the parallel ($\sigma_0$) Hall ($\sigma_H$) and Pedersen ($\sigma_P$) for the mid-latitude daytime ionosphere (dashed curve is typical nighttime profile for $\sigma_P$)
3.5 Magnetic Indices

A magnetic index is a set of discrete values, which characterise a magnetic variation over an interval of time. Four magnetic indices are utilised in this thesis, \( Kp \), \( Am \), \( AL \) and \( Dst \), each of which characterises a different magnetic phenomenon or behaviour.

3.5.1 The \( Kp \) Magnetic Index

The \( K \) index measures the largest range in the horizontal components in a 3 h UT bin recorded by a magnetometer station, with a quiet day removed. The \( K \) index is a quasi-logarithmic scale ranging from 0 to 9 and the index provides an estimate of geomagnetic noise, primarily resulting from auroral activity. \( Kp \) is a planetary index derived from the \( K \) index of 10 northern hemisphere and 1 southern hemisphere mid-latitude stations and is sensitive to auroral activity [Bartels, 1949]. As with the \( K \) index, \( Kp \) is scaled from 0–9, but with increments of −, 0, +. Typically \( Kp \) is in the range 2+ to 3− rising to typically 6 or 7 during storm intervals, reaching 9 only during extremely disturbed periods. Due to the non-uniform distribution of contributing stations, UT variations could not be incorporated into the \( Kp \) index, thus any diurnal variations have been scaled out of the constituent \( K \) indices [see e.g. Mayaud, 1980].

3.5.2 The \( Am \) Magnetic Index

The \( Am \) index is derived from the 3 h \( K \) indices of 15 northern and 11 southern magnetometer stations near ±50° in corrected geomagnetic coordinates, and has been specifically constructed to reflect UT variations in geomagnetic activity [Mayaud, 1967; 1980]. The contributing stations are divided into 8 groups of similar geographic locations which are roughly evenly distributed longitude. From each group an appropriate \( K \) index is extracted, from which the planetary \( Am \) magnetic index is then calculated. The \( Am \) index is expressed in linear form with units nT and a typical value of ~20 nT, although \( Am \) can be several hundred nT during disturbed intervals. The \( Am \) index is sensitive to auroral variations and relatively insensitive to the ring current.

3.5.3 The \( AL \), \( AU \) and \( AE \) Magnetic Indices

The \( AL \), \( AU \) and \( AE \) magnetic indices are generated by the envelope of the superimposed
1 min averages of the $H$ component of data from 12 auroral magnetometer stations [Davis and Sugiura, 1966]. The $AL$ index is the lower trace of the envelope, with the upper trace forming the $AU$ index and the width of the envelope ($AU-AL$) is the $AE$ index. The $AE$ index is a measure of the global electrojet strength, with $AU$ sensitive to the eastward electrojet and $AL$ sensitive to the westward electrojet. The ideal location for the magnetometer stations which make up the $AE$ and related indices is between corrected magnetic latitudes 68° to 71° [e.g. Mayaud, 1980]. Six of the twelve contributing stations are located within this range (Figure 3.4). There are several limitations of the $AE$ and related indices [see e.g. Baumjohann, 1986]. The angle between the horizontal magnetic field vector (local $H$ direction) and the eccentric dipole north-south direction can exceed 30° for some stations. Since the electrojets flow along the auroral oval rather than perpendicular to the local $H$ direction the electrojet current tends to be underestimated. Longitudinal gaps in the stations exceed 2 h of local time in some cases, and since the substorm current wedge can cover less than 2 h of local time for small substorms, the substorm current system can be missed by the 12 station coverage. During periods of $B_z$ positive, and the growth phases of large substorms, the auroral oval may contract to a radius inside, or expand to a radius outside, the ring of contributing station coverage, underestimating the electrojet. It has been argued that for this reason the $Am$ index is a more reliable measure of auroral activity than $AE$ since the $Am$ index is comprised of observations sufficiently far from the auroral oval as to be unaffected by its movement [Mayaud, 1980]. In addition, a significant part of the north-south component of the magnetic field measured by the contributing stations may stem from strong field aligned currents rather than the electrojets, increasing or decreasing the measured electrojet. In this thesis 1 h averages of the $AL$ index are employed.

3.5.4 The $Dst$ Magnetic Index

The $Dst$ magnetic index is, in principle, a measure of the ring current magnetic field (and also its total kinetic energy content) and, of all the magnetic indices, it probably monitors its intended parameter with the most success [e.g. Mayaud, 1980]. The present $Dst$ index is based on the $H$ component recorded at four low latitude (20° to 30°) magnetometer stations: Honolulu, San Juan, Hermanus and Kakioka [Sugiura, 1964]. The $Dst$ index
Figure 3.4 Map illustrating the location of the 12 magnetometer stations used to construct the $AE$ and related indices. Also illustrated is the horizontal magnetic field vectors (local $H$ direction; solid line) and the geomagnetic north direction (eccentric dipole coordinates; broken line). In some instances the angle between the two directions exceeds 30° [from Baumjohann, 1986].
has units of nT with a typical value of ~20 nT during quiet conditions, but will fall below ~600 nT during particularly large magnetic storms. There are, however, some limitations in the Dst index [see e.g. Mayaud, 1980; Baumjohann, 1986]. There are magnetic contributions in addition to the ring current which will affect the H component of the low latitude geomagnetic field, such as the magnetopause current, the partial ring current and substorm current systems and thus give an inaccurate measurement of the ring current energy. Although the magnetopause current is included in the quiet time reference level which is removed before the construction of the Dst index, the magnetopause current is a function of the solar wind dynamic pressure. Typically the local time magnetic perturbations resulting from magnetopause currents can typically vary between 10 nT to 40 nT during a shock impact of the solar wind upon the magnetosphere [Nishida, 1978]. The partial ring current prevails in the afternoon local time sector and results in a southward perturbation in the geomagnetic field near dusk. Furthermore, Mayaud [1980] pointed out that there is a maximum in the time averaged UT variations in the Dst index at ~1330 UT, the time at which the largest longitudinal gap in the contributing stations is centred on the peak partial ring current. The substorm current system, which dominates at nighttime auroral latitudes, can result in significant north-south perturbations in the low latitude geomagnetic field. In addition, solar wind magnetospheric coupling studies are primarily interested in the rate of energy injected into the ring current. The time constant of dissipation, \( \tau \), however, is a function of Dst and it is therefore difficult to accurately calculate the rate of energy injection from Dst.

The Dst index is in principle proportional to the total kinetic energy of the ring current [e.g. Stern, 1984], and is thus a good measure of storm activity, and has been used by several authors when defining the occurrence of a magnetic storms [e.g. Gonzales and Tsurutani, 1987; Tang, 1989; Tsurutani et al., 1992]. However, Dst may occasionally be limited in use as an indicator or large magnetic storms, since effects associated with storms (e.g. communication disruption and spacecraft charging) may sometimes be severe, but the minimum Dst perturbation may be small [Lanzerotti, 1992; Boteler, 1993].
3.6 Summary

A wide variety of data sources varying from ground based radar and magnetometer of satellite borne instrumentation has been described. Data from these sources form the basic observations upon which all the analysis has been based.
CHAPTER 4
Magnetospheric and Ionospheric Convection
During the Magnetic Storm of March 20–21 1990

4.1 Introduction
The first detailed investigation is a multi-instrument case study of the global ionospheric convection and magnetic response during a magnetic storm which results from unusually perturbed conditions in the solar wind energy input. These results are compared with observations made under more normal solar wind conditions. The magnetic storm occurred on 20–21 March 1990 (day 79/80), and has been selected for detailed study as part of the Coupling Energetics and Dynamics of Atmospheric Regions (CEDAR) Storm programme [Buonsanto and Foster, 1993]. Two particular intervals have been identified by ground magnetometer and ionospheric activity. The first interval includes the storm sudden commencement (SSC) at 2243 UT on March 20 [Solar-Geophysical Data, 1994] and lasted until ~0700 UT on March 21. The second interval starts with the resumption of solar wind and IMF data from the IMP–8 spacecraft at ~1100 UT and encompasses a secondary increase in ionospheric convection in response to a southward turning of the IMF at 1318 UT on March 21. This chapter considers three main sub-topics: (1) the ionospheric convection and magnetic response times to the southward turning accompanying the shock front in the solar wind pressure during interval 1 and the southward turning of interval 2; (2) the relation of the size of the polar cap boundary to the prevailing conditions in the IMF; and (3) the effect of substorm activity on the nightside convection pattern.

4.2 The Data
The instrumentation employed in this study are described in Sections 3.2 to 3.4 comprising Wick and Goose Bay (GB) coherent radars, Sondrestrom, EISCAT and Millstone Hill (MH) incoherent scatter radars, Goose Bay, Millstone Hill and Qaanaa
digisondes and 44 individual magnetometer stations comprising of the USGS, SAMNET, BGS and EISCAT cross magnetometer stations in addition to 14 Russian stations.

4.3 Interval Overview

Prior to the SSC, $Dst$ (Figure 4.1) was relatively active reaching a value of $<-50$ nT four hours before the SSC. During the main phase of the storm of 20–21 March 1990, $Dst$ fell below $-130$ nT then took ~3 days to return to its prestorm value. To set this storm in context, the minimum $Dst$ deviation during this storm was the sixth largest of all the storms which occurred during 1990 (defined by $Dst$ falling below $-50$ nT for four consecutive hours). Of the 30 magnetic storms which occurred during 1990 the minimum $Dst$ measured was $-278$ nT which was considerably less than the minimum $Dst$ of $<-600$ nT during the great storm of March 1989. The storm under investigation is, therefore, a large magnetic storm, but not a great storm [e.g. Crooker et al., 1992].

4.3.1 Solar Wind and IMF

Before discussing in detail the ionospheric convection and magnetic response during the two main intervals of interest, it is instructive to consider the solar wind and IMF conditions and the general response of the ionosphere and magnetosphere for the larger interval. Over the 36 h period, 1200 UT March 20 to 2400 UT March 21 there was a 9 h gap in the IMP-8 data from 0200 UT to 1100 UT on 21 March. The spacecraft was initially at GSE $X$, $Y$, $Z$ coordinates of 19 $R_E$, 21 $R_E$ and 13 $R_E$ respectively at 1200 UT on March 20 and finally crossed the bow shock at about 2130 UT on March 21, following a number of brief crossings during the previous hour or so. From 1200 UT the IMF magnitude, $B_y$ (Figure 4.2, panel a) remained positive and reasonably steady at $-10$ nT, apart from the interval $-2100$ UT to $2130$ UT when it was briefly negative. The $B_y$ component (Figure 4.2, panel b) was somewhat variable, but predominantly negative, apart from the three intervals 1200 UT to 1245 UT, 1950 UT to 2045 UT and 2120 UT to 2200 UT. The $B_z$ component of the IMF (Figure 4.2, panel c) was southward until approximately 2100 UT. From 1200 UT on March 20 until the passage of the shock front at 2246 UT, $B_z$ remained reasonably steady at $-10$ nT. The solar wind temperature, $T_{SW}$, was $-50 \times 10^3$ K (Figure 4.2, panel c). At 1200 UT, the solar wind density, $\rho_{SW}$, was
Figure 4.1 Plot of $D_{st}$ from March 19 (day 78) to March 25 (day 84) 1990, including the SSC at 2243 UT on March 20 (day 79).
Figure 4.2 Summary time series plot from 1200 UT, on March 20 to 2400 UT on March 21 indicating an SSC at 2243 UT on March 20 and a southward turning on March 21, showing: a) IMF $B_x$; b) IMF $B_y$ component; c) IMF $B_z$ component; d) IMF $B_t$; e) solar wind temperature, $T_{sw}$; f) solar wind density, $\rho_{sw}$; g) solar wind velocity, $v_{sw}$; and h) solar wind dynamic pressure, $P_{sw}$. 
enhanced at \( \sim 30 \text{ cm}^{-3} \), until \( \sim 1400 \text{ UT} \) when it fell to a more normal \( 15 \text{ cm}^{-3} \) (Figure 4.2, panel f). There was no similar enhancement in the solar wind velocity, \( v_{sw} \), at 1200 UT, which was stable at \( 350 \text{ km s}^{-1} \) until \( \sim 2000 \text{ UT} \) when it slowly climbed to \( 500 \text{ km s}^{-1} \) by 2100 UT (Figure 4.2, panel g). The solar wind pressure, \( P_{sw} \), was, however, reasonably constant at \( \sim 4 \text{ nPa} \) during the interval leading up to the shock (Figure 4.2, panel h).

At 2246 UT a shock front passed the spacecraft resulting in a four-fold increase in the solar wind dynamic pressure to \( 18 \text{ nPa} \). The solar wind density had increased from \( \sim 10 \text{ cm}^{-3} \) to \( 30 \text{ cm}^{-3} \) whilst the solar wind velocity increased from \( \sim 500 \text{ km s}^{-1} \) to \( \sim 600 \text{ km s}^{-1} \) and the solar wind temperature increased by a factor of 2 or more. This suggests the passage of a shock front, as kinetic energy was converted into thermal energy in the plasma [Colburn and Sonnet, 1966]. At the time of the increase in the solar wind pressure the IMF magnitude doubled to \( 20 \text{ nT} \). Furthermore, the \( B_z \) component turned southward, becoming \( \sim 10 \text{ nT} \) and ultimately \( \sim 20 \text{ nT} \) at 2346 UT.

Following the shock front, the solar wind pressure remained at \( \sim 15 \text{ nPa} \) until about 0000 UT, where after it decreased to about \( 7 \text{ nPa} \) by 0200 UT (although only one datum was available), the beginning of the data gap. The IMF magnitude remained at a value larger than \( 10 \text{ nT} \) until 0145 UT when it decreased to \( \sim 5 \text{ nT} \), remaining so until the data gap. The \( B_z \) component gradually became less negative after 2346 UT and turned northward for a brief interval between \( \sim 0030 \text{ UT} \) and \( \sim 0100 \text{ UT} \). Another interval of southward IMF followed, with a value of \( \sim 15 \text{ nT} \) being reached at 0130 UT. By the time of the data gap, however, \( B_z \) had turned northward again. The \( B_x \) and \( B_y \) components oscillated rapidly between positive and negative immediately after the shock, indicative of the passage of a CME [e.g. Lindsay et al., 1994], with the only sustained interval of a single polarity occurring between \( \sim 0015 \text{ UT} \) and \( \sim 0130 \text{ UT} \).

Solar wind and IMF data resumed at \( \sim 1100 \text{ UT} \). \( B_t \) was \( 15 \text{ nT} \), \( B_x \) and \( B_z \) were both \( \sim 10 \text{ nT} \), \( B_y \) was \( \sim 10 \text{ nT} \) and the solar wind pressure was \( \sim 5 \text{ nPa} \). At 1325 UT a rotational discontinuity in the IMF occurred, with \( B_t \) remaining constant as \( B_y \) and \( B_z \) rotated to \( \sim 10 \text{ nT} \) and \( \sim 7 \text{ nT} \) respectively. \( B_x \) remained predominantly negative for the remainder of the day, although with a low magnitude of \( \sim 5 \text{ nT} \) between \( \sim 1500 \text{ UT} \) and
By turned, and then remained negative, $\sim -10$ nT, at $\sim -1500$ UT. At 2130 UT the spacecraft finally crossed the bow shock characterised by the sharp increase in the measured $B_y$ from 10 nT to 25 nT.

4.3.2 Magnetospheric and Ionospheric Response

Ground magnetometers recorded disturbed activity prior to the shocked impact of the solar wind upon the magnetopause observed at 2246 UT by IMP-8, with GML and NEW measuring perturbations of $\sim 50$ nT (Figure 4.3, panels a and b), indicative of enhanced electrojets. An SSC occurred at 2243 UT in response to the shock in the solar wind plasma recorded by IMP-8 at 2246 UT, which was also coincident with a southward turning in the IMF and an enhancement in the field magnitude. Following the SSC the level of magnetic noise increased considerably, remaining highly disturbed for the remainder of the interval under study.

Prior to the SSC at 2243 UT ionospheric flow measurements indicated enhanced convection. EISCAT measurements of the ionospheric convection began at 1530 UT ($\sim 1730$ MLT; Figure 4.3, panel c) at which time the convection flow magnitude was $\sim 1000$ m s$^{-1}$. The flow then decreased steadily to near zero by 1900 UT ($\sim 2200$ MLT) suggesting that the radar had passed into the region of the nightside flow reversal. The Wick radar recorded coherent backscatter from 1400 UT ($\sim 1530$ MLT; Figure 4.3, panel d), until $\sim 2000$ UT (2130 MLT) also suggesting that by that time the radar had moved into the region of the nightside flow reversal. The Goose Bay digisonde recorded enhanced westward flow from 1615 UT ($\sim 1315$ MLT; Figure 4.3, panel e) which peaked at 1800 UT ($\sim 1500$ MLT) and the Millstone Hill radar recorded high ion flows which peaked at $\sim 1500$ m s$^{-1}$ at latitude 71°N at 2030 UT ($\sim 1530$ MLT; Figure 4.3, panel f).

All instruments measured a change in activity following the impact of the shocked southward turning of the IMF on the magnetosphere: EISCAT recorded enhanced eastward ion flows reaching 1000 m s$^{-1}$ at $\sim 2400$ UT (0200 MLT); Wick recorded the onset of backscatter with flow away from the radar at 2249 UT (0019 MLT); and the flow observed by both the Goose Bay digisonde and Millstone Hill radar reversed direction from eastward to westward. The ion velocities measured by EISCAT, the irregularity phase speeds measured by Wick and the flow velocities inferred by the GB
Figure 4.3 Summary time series plot from 1200 UT, on March 20 to 2400 UT on March 21 indicating an SSC at 2243 UT on March 20 and a southward turning on March 21, showing: a) GML $H$ component, at 55° N; b) NEW $H$ component, at 55° N; c) EISCAT eastward ion drift velocity at 66° N; d) Wick line of sight irregularity phase speed at 64° N; e) Goose Bay digisonde eastward flow velocity; at 62° N f) Millstone Hill eastward ion drift velocity at 70° N.
digisonde continued to be high until ~0600 UT. The ion velocities measured by Millstone Hill, which was in the pre-midnight local time sector at the time the shock reached the magnetopause, remained high until ~1100 UT (~0600 MLT). The velocities measured by EISCAT remained low from 0600 UT to 1330 UT and then increased, reaching ~2 km s\(^{-1}\) at 1530 UT. Backscatter returned to the Wick f-o-v at about 1330 UT (~1500 MLT) reaching a maximum of 500 m s\(^{-1}\) at 1400 UT. The flow measured by EISCAT reversed sign at ~1800 UT and again at ~2000 UT and ~2200 UT. The l-o-s velocity measured at Wick did not reverse sign until ~2300 UT. Flow velocities measured by the Goose Bay digisonde and Millstone Hill radar were enhanced between ~1700 UT to 1930 UT and ~1900 UT to 2100 UT respectively. The response of the magnetosphere and ionosphere during the interval 1100 UT to 2200 UT is discussed in more detail later in the chapter.

In summary, during these 36 h, there were a number of intervals of significant activity. One occurred prior to the passage of a shock in the solar wind and one was directly in response to the passage of a shock in the solar wind. A third interval of high activity also occurred, but in this case due only to an interval of southward IMF. Attention is focussed on the latter 2 intervals for the remainder of this chapter.

4.3.3 Geometry of Bow Shock

Figure 4.4 illustrates the geometry of the Earth’s bow shock (deduced from the normalised empirical models of Nemecek and Safronková [1991] for the Z=0 plane) looking down upon the north pole of the Earth. The location of the IMP-8 spacecraft at both the time the solar wind dynamic pressure shock struck the bow shock and at the time at which the southward turning recorded at 1325 UT impinged upon the magnetopause is also illustrated in Figure 4.4. The inferred plane of propagation of the shock front and IMF Z component discontinuity deduced from a detailed study of timings are included in the figure. The plane of propagation of both the shock front and the \(B_z\) discontinuity are at an angle of ~45° with the \(X\) (GSE) axis. Since the phase front and the shock are both perpendicular to the Parker spiral, it is implied that both discontinuities result from temporal changes in the "emitted" solar wind and IMF rather than spatial changes, such as a high/low speed stream interface, which would result in a discontinuity along the Parker
Figure 4.4 Map presenting the inferred geometry of the shock front of the SSC at 2246 UT on March 20 and the phase front of the southward turning during at 1325 UT on March 21. The geometry of the bow shock has been deduced from the empirical models of Němeček and Šafráňková [1991] (see text for details). The plane of the shock and the phase front of the southward turning reach the magnetopause 6 min and 9 min (respectively) prior to detection by the IMP-8 spacecraft.
4.4 Observations: Interval 1 (2200 UT, March 20 to 0700 UT, March 21)

4.4.1 Ground Magnetometer

Figure 4.5 presents a summary of the $H$ and $D$ magnetic field components observed between 2200 UT, 20 March and 0700 UT, 21 March by seven ground magnetometer stations situated at a geomagnetic latitude of 55 ($\pm 2$)$^\circ$ N and ordered in increasing magnetic local time (MLT). At 2243 UT all stations recorded a storm sudden commencement. The largest increase in the $H$ component occurred at NEW (~1400 MLT; Figure 4.5a). The magnitude of the SSC slowly decreased toward magnetic midnight. Stations in the dawnside, YAK and MGD at ~0700 MLT and 0800 MLT recorded decrease of the $H$ component. The $D$ component, however, is in general the reverse of the $H$ component in both relative amplitude and direction (Figure 4.5b). All stations subsequently measured perturbed activity, with large negative bays in excess of 300 nT in the $H$ component (Figure 4.5a) in the western European sector.

Also included in Figures 4.5a and b (bottom panels) are band passed filtered data between 5 mHz and 50 mHz from the SAMNET station GML to emphasise Pi2 wave activity, a classic signature of substorm expansion phase onset [Rostoker et al., 1980]. Pi2 pulsations indicate that substorm expansion phase onsets occurred at 2313 UT, 2327 UT, 2350 UT, 2400 UT 0210 UT and 0220 UT. Inspection of bays in magnetograms recorded in the Russian and American stations also suggest further substorm expansion phase onsets at 0036 UT, 0112 UT, 0141 UT and 0610 UT, although there is no evidence of wave activity in the SAMNET data.

4.4.2 Ionospheric Flow

Measurements of ionospheric convection are represented in the form of polar plots as a function of MLT and magnetic latitude in Figure 4.6. Each polar plot presents short time series of ionospheric flow measurements along meridians by the radars and digisonde at the appropriate MLT and latitude for a specific interval of UT, with blue (red) vectors indicating eastward (westward) flow. The solar wind and IMF data averaged over the
Figure 4.5  Ground magnetometer plots of 7 mid latitude stations (at ~55° N) from the interval 2200 UT March 20 to 0700 UT March 21 presenting the SSC at 2243 UT (broken red line). The bottom panel presents 5 ms to 50 ms band pass filtered GML data illustrating Pi2 wave activity which are indicative of substorm expansion phase onsets. Substorm expansion phase onsets identified from Pi2 waves and additional expansion phase onsets identified from bays in data from Russian and European stations are also shown (green broken lines) for a) $H$ components; and b) $D$ components.
Figure 4.6 Polar plots in IGRF magnetic latitude and MLT presenting a short interval of ionospheric flow vectors for the ionospheric radars and digisonses illustrated in Figure 1. See text for details. The figure also includes the averaged solar wind and IMF conditions for the interval: a) 2140 UT to 2243 UT on March 20; b) 2243 UT to 2350 UT; c) 2350 UT to 0036 UT; d) 0036 UT to 0113 UT; e) 0113 UT to 0141 UT; f) 0141 UT to 0220 UT; g) 0220 UT to 0300 UT; and h) 0300 UT to 0400 UT.
relevant period of UT are given next to each plot. In the hour prior to the SSC (Figure 4.6a; 2140 UT to 2243 UT) radars in the afternoon/dusk convection cell observe westward flow between 300 m s$^{-1}$ and 500 m s$^{-1}$ at latitudes greater than 65°N, and low eastward velocities (<100 m s$^{-1}$) at lower latitudes. No backscatter was detected by either Goose Bay, at ~1900 MLT, or Wick at ~2300 MLT, during this UT interval. EISCAT at 0100 MLT recorded weak flows of ~200 m s$^{-1}$ in a primarily eastward direction indicative of the return flow in the dawn convection cell. The solar wind velocity and density were normal during this interval (mean values of 479 km s$^{-1}$ and 9 cm$^{-3}$ respectively), with $B_z$ northward at +4 nT, following the change in polarity at 2100 UT, and a total IMF of 9 nT.

In the hour following the SSC, ionospheric flow activity increased considerably (Figure 4.6b; 2243 UT to 2350 UT). This interval also included the first two substorm onsets or intensifications, at 2313 UT and 2327 UT, identified by Pi2 pulsations at GML. The MH radar, near 1900 MLT, measured strong westward flow between latitudes 52°N and 67°N, but eastward flow between 67°N and 70°N. Inspection of the I-o-s MH radar data suggest that the velocity enhancements at lower latitude occurred between 2245 UT and 2247 UT. The MH digisonde recorded an increase in velocity beginning at 2245 UT (1742 MLT), measuring equatorward flow of ~300 m s$^{-1}$. The Goose Bay radar (~2100 MLT) recorded strong, but patchy backscatter which was consistent with equatorward flow of ~1000 m s$^{-1}$ commencing at 2316 UT (~2015 MLT). Wick first detected backscatter at 2249 UT (~0019 MLT), with the flow direction away from the radar initially ~100 m s$^{-1}$, then increasing to ~400 m s$^{-1}$ by 2334 UT (~0104 MLT). EISCAT measured generally southeastward ion velocities of ~1000 m s$^{-1}$. Between 2350 UT and 0036 UT, (Figure 4.6c), the ionospheric convection remained very similar. The MH radar (~2000 MLT) observed eastward flow at latitudes above 66°N and westward flow below. The GB digisonde (~2100 MLT) also measured eastward flow, consistent with Millstone Hill, but backscatter at the Goose Bay radar had disappeared. Wick (~0100 MLT) continued to measure flow away from the radar and EISCAT (~2100 MLT) measured eastward flow. The Qaanaaq digisonde recorded data from
0000 UT on March 21, initially measured antisunward flow of \(-250\) m s\(^{-1}\) along the 2130 MLT meridian.

The intervals in Figures 4c to 4g (2350 UT to 0300 UT) represent the time between successive substorm intensifications, with the start time for each panel equivalent to the expansion phase or intensification onset time. Substorm expansion phase onsets have been identified 2350 UT, on March 20 and 0000 UT 0036 UT, 0112 UT, 0141 UT, 0210 UT and 0220 UT on March 21. Throughout these intervals the EISCAT and Wick velocity measurements are all consistent with eastward flow in the dawn local time sector.

During the same interval, apart from the observations at 0015 UT, the MH radar velocity measurements are predominantly of westward flow, \(ie.\) sunward flow in the dusk local time sector. Measurements by the GB radar, however, do show variations in each panel. Between 2350 UT and 0036 UT (Figure 4.6c) there was no backscatter observed by Goose Bay. In the next interval, 0036 UT to 0113 UT (Figure 4.6d), the observations are primarily equatorward as in the case of the next interval, 0113 UT to 0141 UT (Figure 4.6e). However, over the next \(-40\) minutes, 0141 UT to 0220 UT (Figure 4.6f), the Goose Bay measurements are predominantly eastward at latitudes above 70° N and westward at latitudes near 63° N. Figure 4.6g covers an interval from 0220 UT to 0300 UT, which began with the last of the substorm intensifications. During this interval the measurements by the Goose Bay radar are predominantly southwestward at all latitudes although there are some eastward flow measurements below 70° N.

Finally during the following hour, 0300 UT to 0400 UT, (Figure 4.6h), when there is no identified substorm activity, the MH observations at 2200 MLT are of westward flow and the Goose Bay measurements near magnetic midnight are of almost purely equatorward flow.

4.5 Discussion: Interval 1 (2200 UT, March 20 to 0700 UT March 21)

There have been a number of previous studies of the response of ionospheric convection to solar wind conditions and have either been statistical in nature \(e.g.\) de la Beaujardiere et al., 1986; Etemadi et al., 1988, or case studies \(e.g.\) Lockwood et al., 1986; Lester et
al., 1993]. Most of these studies have been under fairly typical solar wind and IMF conditions. Interval 1, however, was very disturbed since the first 8 h following the SSC contained at least 9 substorm expansion phase onsets/intensifications. The magnetosphere was highly excited due to both enhanced reconnection on the dayside and a shock front in the solar wind dynamic pressure striking the magnetosphere, resulting in a 200 fold increase in the energy input, $U(t)$, based on the $\epsilon$ energy coupling parameter [Perreault and Akasofu, 1978; Williams et al., 1992]. The following sections attempt to account for the observed ionospheric convection and magnetic response during this interval.

### 4.5.1 Response Times of Ionospheric Convection

The response times of ionospheric convection to changes in the IMF at the subsolar magnetopause have been described in detail in Section 2.2.7. In their study of the nightside response during a substorm growth phase, Lester et al. [1993] concluded that the nightside response varied from ~10 min near dusk to ~40 min near midnight (Figure 4.7, diamond plot symbols).

In the present study, the solar wind conditions are extreme. $B_z$ increased by a factor of 4 at the time of the southward turning to a value greater than 20 nT; $B_z$ peaked at ~20 nT an hour after the SSC; the solar wind dynamic pressure was ~20 nPa for the hour or so following the shock. Thus in addition to the increased efficiency of energy transfer during $B_z$ south there was also additional energy due to the enhanced solar wind pressure and a reconfiguration of the magnetosphere in response to the shock impact of the CME. From knowledge of the time the shock was detected by IMP-8 and the time the SSC was recorded by ground magnetometers, the time for the southward turning impinging on the magnetopause can be deduced accurately. Based upon the empirical models of Nemecek and Safarčková [1991], it is estimated that the southward turning reached the subsolar magnetopause at 2240 (±1) UT. For the incoherent radars and digisondes a threshold value of 400 m s$^{-1}$ was adopted to indicate the onset of activity, whereas, for coherent radars, the detection of backscatter was employed as an indicator of ionospheric response. The Goose Bay radar first detected backscatter at 2316 UT after, and possibly in response to, the onset of the first substorm expansion phase and cannot therefore be used as a measure of the response to the southward turning associated with the SSC.
Figure 4.7  Response times to changes in at the subsolar magnetopause to the southward turning studied by Lester et al. [1993] at 2222 UT (solid diamond plot symbol); and the southward turning associated with the SSC at 2243 UT during interval 1 of this study (square plot symbols) with Millstone Hill radar (MHR) and digisonde (MHD), Sondrestrom (Sond) low and high latitude, Wick and EISCAT.
response times to the southward turning at the magnetopause (at 2240 UT) are in the range of 5 min to 20 min for all local times (Figure 4.7; square plot symbols). The measured value of the delay at Millstone Hill (MH) for this interval is of the same order as that during the interval described by Lester et al. [1993] under normal solar wind conditions, although the upper limit response time in the present case under extreme solar wind conditions is half that measured under normal solar wind conditions. The response time measured at Wick, however, is considerably reduced from 45 (±5) min measured under normal solar wind conditions down to 10 (±2) min. The EISCAT measurement [17 (±4) min] is also a factor of 2-3 quicker than that measured under normal solar wind conditions [40 (±20) min] although it is in agreement within the uncertainty. The large uncertainty in the EISCAT measurement employed by Lester and co-workers is due to nature of the CP-3 scan employed at that time. However, it seems likely that the value of 40 min is realistic given the Wick measurements for that interval. Thus the ionospheric response to the southward turning of the IMF during these highly disturbed solar wind conditions at dusk to midnight local time is a factor of 2 less than the response time of the ionosphere to a southward turning under more normal conditions. This implies that a more rapid input of energy into the magnetosphere in the dayside leads to a more rapid response on the nightside.

It is not possible to draw a conclusion as to which factor caused the more rapid nightside response times to the southward turning associated with the SSC. The prevailing solar wind and IMF conditions were different to those of previous studies in three important respects; the IMF Z component was large (initially -10 nT, rising to -20 nT), the solar wind dynamic pressure was considerably enhanced (a result of both enhanced solar wind velocity and density) and there was a rapid increase in the dynamic pressure upon the magnetosphere. One possibility is that the pressure pulse caused a reconfiguration of the magnetosphere which allowed a more rapid transmission of the signal indicating a change in IMF $B_z$. A study of response times of ionospheric convection to changes in $B_z$ under different solar wind plasma conditions is necessary to clarify this point.
4.5.2 Polar Cap Expansion

When \( B_z \) is southward, the IMF reconnects with the geomagnetic field at high latitudes, thereby increasing the area of the polar cap [Section 2.2.2]. Open magnetic flux is subsequently lost during tail or nightside reconnection, resulting in a general contraction of the polar cap. The absolute change in polar cap area, \( dA \), is a function of the balance between opening flux on the dayside, and closing flux on the nightside, with the total change in area determined by Faraday's law. In the fluid model of Siscoe and Huang [1985] the boundary between open and closed field lines is adiabatic (meaning no flow across) except at the dayside and nightside merging gaps. The equatorward expansion rate of the polar cap has been studied during substorm growth phases [e.g. Lockwood et al., 1986; Lester et al., 1990] and found to be consistent with both the expansion velocity predicted using Faraday's law and an adiabatic boundary. The equatorward extent of the polar cap boundary has been determined from Faraday's law and compared with the flow shears observed by the Millstone Hill radar from the time of the SSC to ~0200 UT. Due to the low temporal resolution of the MH velocity data of ~30 min, it has not been possible to relate the observed flow reversals directly to substorm activity since the time between successive expansion phase onsets/intensifications is of the same order as this temporal resolution. Substituting \( t \) from Equation 2.9 into Equation 2.11 gives an expression for the velocity of the polar cap boundary, \( v_{pc} \), in the absence of tailside reconnection, determined by the instantaneous radius of a circular polar cap, \( r \):

\[
v_{pc} = \frac{dr}{dt} = \frac{\phi_d}{2\pi B_p r}
\]

(4.1)

where \( B_p \) is the geomagnetic flux density at ionospheric latitudes and \( \phi_d \) is the dayside reconnection voltage and is related to the cross polar cap potential, \( \phi_{pc} \), by

\[
\phi_d = 2(\phi_{pc} - \phi_s) - \phi_s
\]

(4.2)

where \( \phi_s \) is associated with viscous interactions [Lockwood and Cowley, 1992]. The dayside reconnection voltage can be estimated using Equation 2.1, by equating \( \phi_s = 38 \) kV. The polar cap voltages employed in the empirical study of Reiff et al. [1985a] under conditions of \( B_z \) negative would have contained a contribution from tailside reconnection.
in addition to dayside reconnection, which could in principle contribute to as much as 50% of the measured polar cap voltage. The angle between the IMF and GSM Z axis, $\theta$, the estimated dayside reconnection voltage polar cap potential, $\phi_p$, the expansion rate of the polar cap from Equation 4.1, $v_{pc}$, and the resultant latitude of the polar cap boundary (PCB) between 2230 UT and 2400 UT on March 20 are presented in Figure 4.8. In this plot, $B_p$ is assumed to be $5 \times 10^{-5}$ nT and the PCB was initially set at 75° N. DMSP electric field data [W. Denig, private communication, 1993] and provisional AMIE modelling patterns [D. J. Knipp, private communication, 1993] suggest that the PCB was located at 75° N at -2220 UT. The upper and lower envelopes of Figures 4.8 b to d represent the limits resulting from the extreme values of $\phi_p$ from equation 4.1 assuming no contribution ($\phi_p=0$) and equal contribution ($\phi_p=\phi_e$) from tailside reconnection. After the SSC at 2243 UT, the above model gives an equatorward motion of the PCB of $-300 (\pm 100)$ m s$^{-1}$. By the first substorm expansion phase onset at 2313 UT the model PCB reached 69.5 (±1.5)° N; 68.5 (±2.5)° N at 2327 UT, the subsequent intensification, 66 (±3)° N at 2350 UT and 65 (±3)° N at the 2400 UT intensification. The convection flow reversal boundary observed by MH at 2400 UT was at 67° N, in agreement with the predicted value of the PCB. However, the flow reversal boundary only places a lower limit on the PCB. These calculations assume no open flux was closed during the expansion phase and subsequent intensifications, and indeed recent work has suggested delays of between 10 min and 30 min before open flux is closed following an expansion phase onset [e.g. Gazey et al., 1994; Fox et al., 1994]. Furthermore, 1-o-s Millstone Hill radar data indicate an equatorward flow component of $-500$ m s$^{-1}$ at latitudes where the flow reversal is visible in the processed data. This velocity is of the same order as the predicted value of $-200$ m s$^{-1}$ to $400$ m s$^{-1}$, which within the approximation is consistent with an adiabatic boundary. Thus to within the limitations of these calculations the observed polar cap boundary is in agreement with the model, although a better fit is obtained by assuming the expanding polar cap is elliptical which would result in a higher $v_{pc}$ in the MH radar field of view [e.g. Lockwood 1991a].

Figure 4.9 is a schematic illustration of the resultant expansion of the polar cap following the southward turning at the time of the SSC. The shape of the polar cap is
Figure 4.8 Time series plot from 2230 UT to 2400 UT March 20, presenting a) the angle between the IMF and the Z axis, $\theta$ with the time adjusted to when the feature was at the magnetopause; b) the cross polar cap potential, $\phi$; c) the expansion velocity; and d) the subsequent inferred latitude of the polar cap boundary, with a starting value of 75° N, based on DMSP flow data and provisional AMIE patterns.
Figure 4.9  Schematic illustration of the polar cap expansion into the MH radar’s field of view, with the presented shape based on provisional AMIE model plots at 2325 UT: a) at 2243 UT, prior to the polar cap expansion; and b) at 2327, after the polar cap has expanded into the Millstone Hill radar field-of-view.
based on the provisional AMIE modelling patterns. Prior to the southward turning (Figure 19a) Millstone Hill was observing westward flow at all latitudes with the polar cap boundary at 75° N. However, after non-uniform expansion due to the inflow of dayside flux the PCB had moved to 67° N at the local time of the Millstone Hill field-of-view with the radar measuring westward flow at latitudes >67° N and eastward below at the time of the 2327 UT substorm intensification (Fig 7b). To summarise, convection flow reversals observed in the Millstone Hill radar field-of-view are consistent with the position of the PCB deduced form simple models based on Faraday’s law. In order to fit the data accurately, however, it has been assumed that the expansion is non uniform, resulting in an elliptical polar cap. In addition, the flow reversal boundary is consistent with an adiabatic boundary since the predicted equatorward velocity is of the same order as the measured equatorward ion velocity.

4.5.3 The Nightside Flow Reversal
Figure 4.10a and b repeat the nightside convection pattern from Figure 4.6f and g respectively to illustrate the nighttime flow reversal before and after 0220 UT. Before 0220 UT (Figure 11a) the convection flow reversal was skewed toward the dusk sector, but, directly after 0220 UT (Figure 11b) the reversal was skewed toward the dawn. The location of the nightside flow reversal was determined for the Goose Bay radar data with a temporal resolution of ~10 min. The data indicated that the reconfiguration of the nightside flow reversal occurred on a time scale less than or equal to this integration time since the earliest UT point of GB data in Figure 4.6g lags the last recorded point in Figure 4.6f by 10 min. The patterns of Figures 11a and 11b are consistent with the “banana and orange” averaged convection patterns for \( B_y \) negative and for \( B_y \) positive respectively [e.g. de la Beaujardiere et al., 1986], although no IMF data were available during these intervals. If the reconfiguration resulted from a change in \( B_y \) then the upper limit for the response time of the nightside ionosphere to the change at the magnetopause is 22 min assuming \( B_y \) turned positive at 0201 UT, the start of the IMP-8 data gap. At 0210 UT and 0220 UT substorm expansion phase onsets have been observed from Pi2 pulsations visible in the SAMNET magnetometer data (~0300 MLT). By studying the bays in the USGS, SAMNET, BGS and Russian magnetometer data employing the
Figure 4.10 Schematic illustration of the nightside convection flow reversal superimposed on flow vectors from Figure 4f and 4g for a) before 0220 UT, and b) after 0220 UT on March 21. The figure demonstrates the change from a nightside pattern consistent with models of $B_y$ negative (a) to a pattern consistent with models of $B_y$ positive (b).
method of Lester et al. [1984] the centre of the substorm current systems was deduced to be near 2100 MLT, west of the Goose Bay radar f-o-v. It is not possible, with the available data, to separate the effects on the convection pattern due to possible changes in $B_x$ and the substorm expansion phase onset with the temporal and spatial coverage available. It is conceivable that a change in $B_x$, the substorm expansion phase onset and the reconfiguration of the nightside convection pattern may all be related. The reconfiguration of the nightside convection pattern, however, did occur on a time scale of less than 10 minutes.

4.6. Observations: Interval 2 (1200 UT to 2400 UT March 21)

4.6.1 Ground Magnetometer
Figure 4.11 a and b present the $H$ and $D$ ground magnetic response for 7 stations located near 55° N during interval 2 with the bottom panel presenting 5 mHz to 50 mHz band pass filtered data from the $H$ component of GML, and is the same format as Figure 4.5. All stations measured a resumption of magnetic activity, following the southward turning recorded by IMP-8 at 1325 UT which continues for the remainder of the day. In order to measure the response times of the magnetic activity, a quiet day was subtracted from each station and a threshold of the magnitude of the $HD$ plane with upper and lower limits of 30 nT and 20 nT was adopted. The measured onset times of activity ranged from 1333 (±9) UT at NUR (~1615 MLT) to 1416 (±3) UT measured at MGD UT (~0530 MLT). Figure 4.12 a and b present the $H$ and $D$ components (respectively) of 7 stations, centred near 1600 MLT with a latitude range of ~10°, for the first 3 h of interval 2. Data were recorded at OUL in the $H$ component until 1400 UT and no data were recorded in the $D$ component for the whole of the interval. This was due to saturation of the flux gate magnetometer. To determine the onset times of activity in the meridional chain of Figure 4.12, only the $H$ component was used since no data were available for the $D$ component of OUL and only small perturbations were measured in the $D$ components of the remaining stations. Again a quiet day was subtracted, with upper and lower thresholds of 50 nT and 40 nT adopted in this case. The measured onset times varied from 1331 (±1) UT at SOR (lat. 67.0°N) increasing with decreasing latitude with an onset time of 1346 (±3) UT measured at NUR (lat. 56.6°N).
Figure 4.11 As Figure 4.5 except presenting the interval 1200 UT to 2400 UT, March 21, with the 1314 UT southward turning (ST) at the magnetopause illustrated in red for a) $H$ component and b) $D$ component.
Figure 4.12 Ground magnetometer traces of 7 magnetometer stations situated approximately along a line of magnetic longitude near 1600 MLT; SOR (67.0° N), ALT (66.3° N), KAU (65.5° N), MUO (64.4° N), PEL (63.3), OUL (61.3) and NUR (56.6) for a) $H$ component; and b) $D$ component.
The largest perturbations were recorded in the $H$ components by the western European stations, although little disturbance was visible in the $D$ components of these stations (Figure 4.11). Pi2 pulsations recorded by the SAMNET array (Figure 4.11a and b, bottom panels) suggest that substorm expansion phases occurred at 1848 UT, 1910 UT and 1928 UT, some 5 h to 6 h after the southward turning at the start of interval 2. Earlier pulsations were probably related to dayside ULF waves, and not substorm expansion phase onsets which would be unlikely to be detected by the SAMNET instrumentation in the local time sectors covered in this study. Two further substorm expansion phase onsets have been deduced from bays in Russian magnetometer data at 1420 UT and 1500 UT.

4.6.2 Ionospheric Flow

Figure 4.13 presents polar plots during interval 2 and is the same format as Figure 4.6 with flow vectors from each radar plotted at the appropriate MLT. Prior to the southward turning (Figure 4.13a; 1225 UT to 1318 UT) the Millstone Hill radar, in the morning cell at -0800 MLT measured very weak eastward ion velocities less than 100 m s$^{-1}$. The digisonde at Millstone measured weak equatorward flow, which did not exceed 100 m s$^{-1}$ at any time during interval 2. The GB radar was not operational between 1030 UT and 1353 UT, but GB digisonde (~1000 MLT) recorded weak westward flow of ~50 m s$^{-1}$. Figure 4.13a also includes Sondrestrom data at 1100 MLT, which recorded northeastward ion drift velocities of ~1000 m s$^{-1}$ at 70°N. The Wick radar, at ~1400 MLT, did not detect any backscatter and EISCAT at ~1500 MLT measured weak westward flow of ~200 m s$^{-1}$. Qaanaaq near the north pole measured flow toward dusk. During this interval the solar wind density was 9 cm$^{-3}$, near its pre-SSC values. However, the solar wind velocity was still enhanced at 592 km s$^{-1}$. $B_y$ was strongly negative (~12 nT) and $B_z$ was positive (+6 nT).

The ionospheric convection after the southward turning is presented in Figure 4.13b (1318 UT to 1420 UT). Enhancements in activity were recorded by all instruments at latitudes >63° N, with the Millstone Hill radar observing predominantly
Figure 4.13 As for Figure 4.6 except presenting intervals: a) 1215 UT to 1318 UT; b) 1318 UT to 1420 UT; c) 1800 UT to 1846 UT; d) 1846 UT to 1930 UT; e) 1930 UT to 2015 UT; f) 2030 UT to 2130.
eastward ion flow velocities of ~500 m s\(^{-1}\) at 1340 UT (~0840 MLT) consistent with return flow in the morning cell. The Goose Bay radar at ~1000 MLT detected backscatter with a poleward phase velocity at 1337 UT at latitudes 74° N to 80° N. Sondrestrom, covering a similar \(f-o-v\) to GB continued to measure eastward flow of ~1000 m s\(^{-1}\), but recorded strong poleward flow of ~800 m s\(^{-1}\) from 1400 UT at 80° N, consistent with the antisunward flow measured at Qaanaaq. Wick and EISCAT at ~1600 MLT recorded flow consistent with return flow in the afternoon convection cell, with Wick measuring backscatter from 1345 UT and EISCAT measuring ion velocities greater than 400 m s\(^{-1}\) at ~1333 UT, exceeding 1000 m s\(^{-1}\) at 1336 UT.

Figure 4.13c to f present the convection flow patterns much later during the interval and is associated with the magnetic substorm activity. A substorm expansion phase began at 1846 UT and there were subsequent intensifications at 1910 UT and 1928 UT identified from Pi2 pulsations from the SAMNET magnetometer array. Thus Figure 4.13c considers the ionospheric flow during the interval prior to the first expansion phase, 1800 UT to 1846 UT. All instruments measured flow consistent with their \(f-o-v\) being in the afternoon convection cell, with MH, GB and Sondrestrom radars between ~1400 MLT to ~1600 MLT measuring westward flow at latitudes <68° N. Eastward flow was measured above 68° N, consistent with the antisunward flow measured at Qaanaaq. Initially, both Wick and EISCAT measured flow velocities consistent with return flow in the dusk convection cell. However, after 1830 UT (~2030 MLT) EISCAT measured eastward ion velocities. Figure 4.13d (1846 UT to 1930 UT) represents the ionospheric flows during the initial expansion phase and subsequent intensifications. No flow was measured at latitudes greater than 70° N, but flow consistent with return flow in the afternoon cell was measured by all instruments except for EISCAT which recorded eastward flow. During the subsequent recovery phase (Figure 13e; 1930 UT to 2015 UT) EISCAT measured variable eastward and westward flow while the other instruments recorded similar flow to the previous hour or so. Finally, Figure 4.13f (2030 UT to 2130 UT) presents the interval following the substorm activity. Here EISCAT measured westward flow consistent with return flow in the afternoon convection cell, as was the flow measured by the Wick and Millstone Hill radars. Goose Bay recorded eastward flow
at latitudes greater than 70° N, consistent with antisunward flow in the polar cap.

4.7 Discussion: Interval 2 (1200 UT to 2400 UT, March 21)

4.7.1 Response Times of Magnetospheric and Ionospheric Convection

Following Lester et al. [1993] from knowledge of the spacecraft’s location, the southward turning was estimated to reach the magnetopause at 1314 (±5) UT. A velocity of 400 m s$^{-1}$ was adopted as a threshold value at which the onset of activity was observed by the incoherent radars and the digisondes. Sondrestrom did not consistently measure flow velocities at higher latitudes, and no observable change in flow at 70° N was recorded. The response times to the southward turning at the magnetopause are in the range 20 min to 30 min and are all on the dayside (Figure 4.14; solid diamond plot symbols), with r=0 at 1314 UT and no errors included for the uncertainty in the time at which the southward turning reached the magnetopause. Qaanaaq, situated near the magnetic north pole, measured a rotation in flow direction from duskw ard toward antisunward between 1330 UT and 1345 UT giving a delay of 23.5 (±12.5) min, consistent with the time delays measured on the dayside. Figure 4.14 also includes response times measured from the chain of magnetometer stations at latitudes 55 (±2)° N presented in Figure 4.11, with a threshold of 20 nT to 30 nT in the horizontal plane adopted to determine the onset of activity. The European stations near 1500 MLT to 1600 MLT (NUR and KVI) responded to the changes in $B_y$ at the magnetopause on a time scale between 8 min and 30 min (including the 5 minute error in the time at which the southward turning reached the magnetopause) with stations approaching magnetic midnight measuring increasingly long response times reaching between 55 min and 71 min for MGD at ~2330 MLT.

The response times of the 55° N longitudinally distributed chain of magnetometers exhibit an asymmetry with respect to 1200 MLT, with NEW at ~0600 MLT measuring a response time of 55 min, more than twice the typical response time of ~20 min measured near 1800 MLT. Although with only one station in the morning sector it is not possible to map out the centre of the asymmetry, these results suggest that the minimum response time, and hence the centre of the dayside merging gap, is located post 1200 MLT. IMF $B_y$ was positive following the southward turning. These results are thus consistent with
Figure 4.14 As Figure 4.7, except showing the response time to a southward turning at the subsolar magnetopause at 1315 UT on March 21 1990, with Millstone Hill radar (MHR), Goose Bay radar (GBR), Wick and EISCAT (solid diamond plot symbols) and ground magnetometer responses: NEW, GML, NUR, POD, YAK and MGD.
the displacement of the dayside merging gap for positive $B_y$ described by Cowley et al. [1990] using the dipole plus uniform field model [see Section 2.2.5 and Figure 2.10].

Figure 4.15 investigates the latitudinal dependence. It presents the response times measured from the 7 magnetometer stations of Figure 4.12 roughly in a line of magnetic longitude. Again $t=0$ is taken at 1314 UT, with no error incorporated for the uncertainty in the time at which the discontinuity in the IMF $B_y$ reached the magnetopause. A clear latitudinal dependence is visible, with the highest latitude response time of $\sim 17$ min at $\sim 67^\circ$ N and the lowest latitude response time of $\sim 33$ min at $\sim 57^\circ$ N. A reasonable straight line fit is obtained between the data points with a correlation coefficient of 0.998. These results suggest that for each degree of equatorward latitude the response time of ionospheric convection to changes in $B_y$ at the magnetopause increases between 1 min and 2 min.

The time delays measured by Etemadi et al. [1988] and Todd et al. [1988] employed the EISCAT Polar experiment with viewing positions between 74° N to 79° N. With the exception of Sondrestrom and the top of the GB field of view, these latitudes are higher than those covered in this study. The response times measured by Etemadi et al. and Todd et al. ranged from 10 min to 15 min at 0800 MLT and 1900 MLT to 5 min to 10 min near midday. The response times measured in this study are typically in the range 15 min to 25 min, a factor of $\sim 2$ greater than the studies of Etemadi et al. and Todd et al., although in agreement with the 22 min response measured by Clauer and Friis-Christensen [1988] at latitudes greater than 81° N. In addition, the response time measured at Wick, although consistent with EISCAT, suggests a longer delay before the onset of activity, and indeed enhanced flow was observed earlier at EISCAT than at Wick. The response times given by Lester et al. [1993] are, in general less than the response times measured during this study, with Wick at 0000 MLT (lat. 61° N to 66° N) recording a time delay of $\sim 40$ min to 50 min compared with the measured response time of $\sim 50$ min to 70 min for MGD (lat. 55° N) close to midnight in this study. Furthermore, in the study of Lester et al. the delay measured by Sondrestrom at low latitude ($\sim 70^\circ$ N) was between 20 min and 40 min compared to approximately 1 min to 20 min at higher latitudes ($\sim 78^\circ$ N). These results are in agreement with the latitudinal dependence deduced from magnetometer data (Figure 4.15), with a typical increase in the response time of order
Figure 4.15 Response times as a function of latitude for the 7 ground magnetometer stations of Figure 4.13.
1 min to 2 min per degree of latitude equatorward.

Care must be taken when comparing the different data sets measured above since the criteria for onset varies between data sets. For example the onset for coherent radars was taken as the time at which backscatter was first detected, whereas the onset for incoherent radars was taken as the time at which the ion drift velocity exceeded a certain threshold (400 m s⁻¹). The magnetometer stations measure a separate parameter altogether, and although the magnetic response and ionospheric responses are intrinsically related, human judgment is required to determine the appropriate threshold criteria for each. This is apparent for the latitudinal dependent study in which the magnetic response time was determined according to different criteria. A higher threshold was adopted for the meridional study, but only considering changes in the $H$ component. The quiet day variation in the $H$ component of both SOR (67° N) and NUR (57° N) is 50 nT (in fact the quiet day variation is relatively invariant for the whole of the Scandinavian chain). Following the southward turning the amplitude of response varies considerably between stations, with a minimum at NUR of 260 nT and a maximum of 613 nT at PEL (63.3°N). A lower threshold could not be adopted for the stations in Figure 4.15 because of the amplitude of the noise in the magnetic field at the higher latitudes (OUL and above). The observed delays, however, appear reasonable, although an absolute comparison with the lower latitude chain centred on 55° N is not possible.

4.7.2 Convection Flow Reversal in Wick and EISCAT Field-of-Views

Figure 4.16 presents time series of flow vectors from 1800 UT to 2100 UT from Wick (lower panel) and EISCAT (upper panel). The times of 3 substorm expansion phase onsets at 1846 UT, 1910 UT and 1928 UT are indicated on Figure 4.16 by green vertical dashed lines. This figure demonstrates that in addition to the flow reversals observed by EISCAT prior to the 1846 UT substorm activity, Wick also observed flow reversals in its field of view at high latitudes. From about 1840 UT to 1940 UT (~2010 MLT to ~2110 MLT) Wick measured velocities toward the radar at latitudes < 65° N and flow away from the radar at higher latitudes. EISCAT recorded primarily eastward flow between 1815 UT to 2010 UT (~2215 MLT to 2310 MLT) and primarily westward flow either side. This could have been a polar cap intrusion, although magnetometer data does
Figure 4.16 Range time velocity plot of EISCAT ion drift velocity (top panel) and Wick line of sight irregularity phase velocity (bottom panel) from 1800 UT to 2100 UT on March 21, highlighting the convection flow reversal in the EISCAT and higher latitude Wick fields of view. EISCAT is approximately 1.5 h ahead of Wick in MLT.
not show excessive disturbance during this interval. Repeating the procedure for the polar cap intrusion of interval 1 [Section 4.5.2], the polar cap potential, expansion rate and radius have been calculated as a function of time, taking the starting latitude to be 71°N at 1800 UT, inferred from preliminary AMIE patterns [D. J. Knipp, private communication, 1993]. The predicted extent of the polar cap boundary is 69°N at 1846 UT, the time of the first substorm expansion phase. If no flux had been lost during substorm expansion phases and subsequent intensifications the extent of the boundary would have been 66°N at 1928 UT, the time of the second intensification. This is in agreement with the flow measured at EISCAT, but is inconsistent with the flow recorded at Wick, although again the polar cap may have been expanding non-uniformly. The expansion velocity of the model is ~150 m s\(^{-1}\), similar to the observed southward propagation of the flow reversals in the Wick data. In the study by Lester et al. [1990] of a polar cap intrusion into the SABRE f-o-v, the nightside polar cap boundary was observed to retreat poleward at 1700 m s\(^{-1}\) resulting from the explosive release of flux from the magnetotail during a substorm expansion phase. The observed poleward retreat of the flow reversals in this study is, however, of the same order as the southward propagation. Furthermore, the eastward flow recorded by the EISCAT radar was present for ~2 h, longer than previous observations of polar cap intrusions. An alternative explanation is that initially all radars were in the dusk cell until ~2100 UT when the EISCAT and the top of the Wick field of view passed into the dawn cell. At ~1930 UT, probably the result of the 1928 UT substorm intensification, the nightside convection reversal moved eastward such that both Wick and EISCAT returned to the dusk cell before reentering the dawn cell at ~2300 UT. The initial position of the nightside flow reversal would have then been located at ~2130 MLT before moving to ~0030 MLT after the substorm intensification. Employing the method of Lester et al. [1984] the current wedge for the 1910 UT and 1928 UT was found to be in the vicinity of 2200 MLT, similar local times to the nightside flow reversal. To summarise, the convection flow reversal observed at high latitudes in the Wick and EISCAT field-of-views has been interpreted as a reconfiguration of the nightside convection pattern in response to a substorm intensification, supporting the view that the nightside convection pattern is largely determined by substorm activity.
4.3 Summary

Two intervals of ionospheric convection driven by unusually disturbed conditions in the solar wind and IMF have been described. The rate of energy input is different for the two intervals, with the first interval containing the ionospheric and magnetic response to a southward turning in the IMF at the time of the impact of a shocked pulse in the solar wind dynamic pressure on the magnetopause and the second containing the ionospheric and magnetic response to a southward turning during an interval of enhanced solar wind velocity. The nightside response times to the southward turning associated with the SSC was \( \sim 10 \) min, a factor of 2 less than measured in under normal solar wind conditions [Lester et al., 1993] and more in agreement with previously measured dayside response times at higher latitudes [Etemadi et al., 1988; Todd et al., 1988]. The measured magnetic and ionospheric response times to the southward turning during interval 2 are approximately a factor 2 greater than the response times measured in earlier studies at higher magnetic latitudes, and in conjunction with a study of the response times of a meridional chain of magnetometers, it is suggested that the response time increases by 1 min to 2 min for each degree of equatorward latitude between latitudes 56°N and 76°N. There is less evidence of a latitude dependence on the response times during the SSC, with Wick, at a lower latitude, measuring a shorter response time than EISCAT and the MH radar and digisonde measuring similar response times of \( \sim 8 \) min. These results suggest that the response of the magnetosphere or ionosphere can vary considerably from event to event and is governed by the prevailing solar wind and IMF conditions. Further work is required to determine the relative importance of the individual solar wind and IMF parameters.

The convection patterns during both intervals of known IMF are consistent with the earlier work [e.g. Heppner, 1977; Potemra, 1979; Friis-Christensen et al., 1985; Burch et al., 1985; de la Beaujardiere et al., 1986; Burrage, 1988]. For both intervals studied, reconfiguration of the nightside pattern have been observed. During interval 1, at 0220 UT, the nightside convection pattern shifted from a configuration associated with negative \( B_y \) to a pattern associated with positive \( B_y \) [e.g. de la Beaujardiere et al., 1986], although no IMF data were available during this interval. A reconfiguration of the nightside convection pattern was also observed during interval 2 near 1930 UT, with the
location of the convection reversal observed moving eastward from ~2030 MLT to ~2330 MLT. Substorm expansion phases were associated with both reconfigurations. Although, superficially, these two events may seem similar, there are subtle differences between them. The observed reconfiguration during interval 1 resulted in little movement in the nightside flow reversal at latitudes ~60° N to 65° N remaining constant at ~2330 MLT. However, a movement in the nightside flow reversal was observed at these latitudes during the reconfiguration of interval 2. In addition, the substorm current system during the reconfiguration in interval 1 was east of the nightside flow reversal at all times, whereas the substorm current system during the movement of the flow reversal in interval 2 was at similar local times to the inferred location of the nightside flow reversal. One final difference, which due to the gap in IMP-8 data during interval 1, is only speculative, is that the reconfiguration of the nightside convection pattern during interval 1 may also be associated with a change in the sign of $B_y$ whereas the nightside pattern observed during interval 2 was primarily driven by a current system associated with a substorm expansion phase.
A Superposed Epoch Analysis of Geomagnetic Storms

5.1 Introduction

The purpose of a superposed epoch analysis of signatures from a large number of magnetic storms is to average intervals of storm time data from a wide variety of points in a solar cycle in order to remove statistical fluctuations and reveal underlying trends in interplanetary and geomagnetic parameters. This study has been broken down into subcategories depending on the degree of geomagnetic disturbance (based initially on Dst), characteristics of solar wind and IMF parameters, and whether the storm was initiated with a sudden or gradual commencement. A sudden commencement storm is characterised by a step function in the data in a global selection of ground magnetometer data followed by a period of enhanced magnetic activity, whereas the gradual commencement storms are indicated with a slow increase in the magnetic perturbation.

For the purposes of this study 1 h resolution data of solar wind and IMF parameters, 1 h averages of geomagnetic indices Dst and AL and the 3 h resolution geomagnetic index Kp, are employed. This analysis provides the gross characteristics of the solar wind and magnetosphere immediately before and during magnetic storms.

5.2 The Database and Analysis Technique

The database studied was provided by WDC-C1 at the Rutherford Appleton Laboratory in the UK. The IMF and solar wind data were recorded by a variety of spacecraft between November 1963 and June 1991 [Section 3.2]. The data have been averaged over 60 minutes. There are many data gaps, which cover ~50% of the interval under investigation. The Geocentric Solar Magnetospheric (GSM) coordinate system [Russell, 1971] is adopted. The advantage of this system is that it describes the IMF in the frame of reference of the Earth’s own magnetic dipole axis and it is therefore a suitable frame
for comparison between the IMF and geomagnetic activity.

For a study such as this, the optimum position of the spacecraft recording the IMF and solar wind data is on the Sun-Earth line fairly close to the magnetopause upstream of the bow shock, otherwise the spacecraft data may represent a region of the solar wind which is different to that impacting on the magnetosphere. With the exception of ISEE-3, all spacecraft were in orbit about the Earth and thus near this optimum position for only a small percentage of the time. ISEE-3, however was in a halo orbit near the Lagrangian neutral point, but suffers from the disadvantage that it was 260 R_E upstream of the Earth. It is thus uncertain whether the measured plasma would strike the Earth’s magnetosphere. However, no attempt has been made to select the data on the basis of the spacecraft position as this would have significantly reduced the available database.

To investigate the response of the magnetosphere three magnetic indices have also been included in the analysis via $A_L$, $K_p$ and $D_{st}$. $A_L$ measures the maximum negative deviation of the $H$ component along the auroral zone. It is the lower band of the envelope of the superimposed magnetometer traces from which $A_E$ is generate and it is a measure of the magnetic activity generated by the westward electrojet in the midnight and morning sectors [Section 3.5.3]. There are however a large number of data gaps (1963-1965, 1976-1977, 1987-1991). The $K_p$ index is a measure of the change in the Earth’s field during a three hour interval derived from data from a dozen magnetometer stations at mid latitudes and spaced around the globe [Section 3.5.1]. $D_{st}$ is generated from four low latitude magnetic stations and is an indication of the activity of the ring current [Section 3.5.4].

Storm intensities have been divided into two classifications according to the $D_{st}$ index: in class 1, $D_{st}$ must be lower than $-100$ nT for four consecutive hours following the onset of the storm; in class 2, the minimum $D_{st}$ must be in the range $-50$ nT to $-100$ nT for four consecutive hours. Consideration of four consecutive hours of data in the definition of storms ensures that the peak level of activity which classifies the storm was representative of the overall $D_{st}$ activity during the main phase of the storm. $D_{st}$ is an imperfect indicator of large magnetic storms [Lanzerotti, 1992; Boteler, 1993] since effects associated with storms (e.g. communication disruption and spacecraft charging) may sometimes be severe but the minimum $D_{st}$ perturbation may be small. However, any errors resulting from such misclassification of storms are likely to be small with
such a large data set. Storms were further classified either as storm sudden commencements (SSC) or storm gradual commencements (SGC). A SSC was defined by inclusion in the Storm Sudden Commencement section of "Solar-Geophysical Data" published by the NOAA, Department of Commerce, USA and an SGC defined as any other storm which had a $D_{st}$ minimum of less than $-50$ nT for four consecutive hours. The terms SSC and SGC used in this chapter and Chapter 6 refer to the storm as a whole and not simply the onset. A further investigation based upon the sign of the $B_z$ component directly after the storm onset has also been undertaken. The aim of this study was to isolate those storms for which dayside reconnection was present at the onset, and those which must have been initiated by a different process.

To identify the time of a storm onset, at least two stations were required to report a synchronised onset in the Principal Magnetic Storms sections of "Solar-Geophysical Data". This method of identifying onset times is imperfect for SGCs since the selection of stations reporting magnetic storm onsets for inclusion in "Solar-Geophysical Data" are biased toward the western hemisphere (ie. Europe and the Americas). There is, therefore, a danger that a storm which first manifests itself over, for example, Asia may not be reported by two appropriately placed stations, and thus the onset time would be taken at a later time when it was detected by western stations. This would result in the smearing of any changes at the time of onset and is considered in more detail in Sections 6.3.3 and 6.4.3.

The onset time of each storm is defined as $t=0$ and a superposed epoch analysis was undertaken for the interval which began two days before and continued for five days after the event. The median and the upper and lower quartiles of the distribution of each parameter were then plotted. The median and upper and lower quartile values were adopted in preference to the mean and standard deviation as they contain information about the shape of the distribution. A significance test has also been undertaken for the mean values at each hour epoch with respect to the point at $t=-48$ h. A confidence level of 0.990 was adopted in this test.
5.3 Results

5.3.1 Superposed Epoch of All Storms

Figure 5.1 illustrates a superposed epoch plot of the directly measured parameters for all 538 storms which occurred between 1963 and 1991 and for which solar wind and IMF data were available. The solid line represents the median value and the broken lines the upper and lower quartiles of the distributions. These plots are not intended to represent individual storm behaviour and as a result of the different storm durations high time resolution features such as substorm activity are smeared out. However this presentation is helpful in establishing the underlying relationships between various solar wind and magnetic parameters. Table 5.1 summarises the times taken from the onset at $=0$ for the input parameters to return to their prestorm value ($t_f$) and the time taken for this parameter to reach its maximum deviation ($t_2$). With the exception of $B_x$, $B_y$, and $B_z$ (Figure 5.1, panels a,b,c respectively) all parameters exhibit skewed distributions, with the upper and lower quartiles of the distribution not spaced symmetrically about the median, with the skew becoming more pronounced after $t=0$ for the majority of parameters. Prior to the onset at $t=0$, all parameters are not significantly different from the median of all the data taken over the 27 year interval. The median values of the radial, $B_z$, and azimuthal, $B_y$, components of the IMF (Figure 5.1, panels a and b) do not significantly deviate from 0 nT throughout the whole superposed epoch, although there is a small negative perturbation in the median $B_y$ directly after $t=0$, which is reminiscent of the passage of an interplanetary sector boundary. However, there is no similar signature in the $B_z$ component which would be expected for a sector structure change. In addition, given the length of the data set, it would be expected that there would be an equal number of sector structure changes where $B_y$ reverses polarity from positive to negative to those where $B_y$ goes from negative to positive. The median $B_z$ (Figure 5.1, panel c) becomes negative for approximately 24 h after $t=0$, reaching $-3$ nT between $t=+4$ h and $t=+15$ h. Directly after the onset at $t=0$, the median $B_y$ (Figure 5.1, panel d) increases from 6 nT to 10 nT within 1 h. This enhanced field with a southward bias implies that $B_z$ (the north south component relative to the Earth's dipole) is important in the generation of magnetic storms. As only $B_x$ and $B_y$ components of the IMF exhibit significant changes during the storms, the $B_x$ and $B_z$ components will not be discussed.
Figure 5.1 A superposed epoch plot showing the median (solid line) and upper and lower quartiles (broken lines) for all storms that occurred between 1963 and 1991 for all directly measured parameters: a) IMF $B_x$; b) IMF $B_y$; c) IMF $B_z$; d) IMF $B_i$; e) Solar wind temperature; f) solar wind density; g) solar wind speed; h) solar wind dynamic pressure; i) AL; j) Kp; k) Dst.
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Table 5.1 Summary table presenting the time between the onset of each class of storm and t1 - the time for the superposed parameters to cease to be significantly different to t = -48 hrs (* indicates that the parameter remained significantly different after 5 days); t2 - the peak in activity of the superposed parameter.
The solar wind is also subject to a rapid change at t=0, with the median temperature (Figure 5.1, panel e) enhanced after the SSC (from $60 \times 10^3$ K to $100 \times 10^3$ K) indicating a shock at t=0 as kinetic energy is converted into thermal energy [Colburn and Sonett, 1966]. The median density (Figure 5.1, panel f) doubles from 8 cm$^{-3}$ to 16 cm$^{-3}$, and the median solar wind speed (Figure 5.1, panel g) increases from 400 km s$^{-1}$ to 500 km s$^{-1}$, resulting in the median dynamic pressure (Figure 5.1, panel h) rising from 2 nPa to 6 nPa. The implication is that many storms are initiated by a shock front in the solar wind striking the magnetosphere. The solar wind speed, $v_{sw}$, does not return to its prestorm value even after 5 days. This is the same for all classifications of storms (see Table 5.1). The solar wind density falls below its prestorm value at t=+20 h and remains significantly lower for the remainder of the 5 day interval after the onset. The resultant pressure, however, ceases to be significantly different from $t=+48$ h at $t=+52$ h. This implies that for several days after the onset the solar wind is a rarefied, faster moving stream with respect to the prestorm conditions.

The geomagnetic response to the change in solar wind and IMF is an enhancement in activity measured by all magnetic indices after the onset. The median AL (Figure 5.1, panel i) falls from $-100$ nT before the onset to $-200$ nT after, reaching a minimum value of $-300$ nT at $t=+12$ h. The median Kp (Figure 5.1, panel j) begins to rise at $t=+3$ h (probably an artifact of the 3 h temporal resolution of the original data) stabilising almost directly after the onset, but reaching a peak at $t=+12$ h of 5-. The median Dst (Figure 5.1, panel k) is subject to a small step at $t=0$ becoming less negative, then drops to a value of $-60$ nT, reaching a minimum value of $-55$ nT at $t=+18$ h. Dst and AL remain significantly different to their prestorm values even after $t=+5$ days, however Kp ceases to be significantly different from its prestorm value after 43 h.

5.3.2 Storm Sudden Commencements (SSCs)

Of the 538 storms identified in this study, 308 have been classified as SSCs, with 126 class 1 (large) and 182 class 2 (small) storms. Figure 5.2 presents a superposed epoch plot for class 2 (small) SSCs during the interval under study. Also included in this plot is an estimate of the energy input from the solar wind injected into the magnetosphere.
Figure 5.2 As for Figure 5.1 but for all small SSCs (see text for details): a) IMF $B_x$; b) IMF $B_y$; c) solar wind density; d) solar wind speed; e) solar wind dynamic pressure; f) solar wind temperature; g) solar wind/magnetospheric energy input rate $U(t)$; h) $A_L$; i) $K_p$; j) $Dst$. 
based on the ε parameter proposed by Perreault and Akasofu [1978]:

\[ U(t) = l_q^2 \nu_m B^2 \sin^2(\theta/2) \mu_0 \]  \hspace{1cm} (5.1)

where θ is the angle between the IMF and the YZ plane and \( l_q \) is the effective width of the magnetosphere and has been equated to 25 R_E [Williams et al., 1992]. Unlike the average for all storms there is no sustained negative bias in the median \( B_z \) for the first 24 h after \( t=0 \) (Figure 5.2, panel a). That is to say that on for any given hour after \( t=0 \), the \( B_z \) component is equally likely to be positive as it is negative in agreement with the long term average of this component. This does not mean that there is no enhanced reconnection occurring in this class of storm since the \( B_z \) distribution of values is much broader for this class of storm with the quartiles at ±4 nT directly after the onset compared to ±2 nT before for all storms. The median \( B_z \) (Figure 5.2, panel b) undergoes a rapid enhancement from 6 nT prior to the onset, to 12 nT at \( t=+1 \) h. The solar wind density increases from 9 cm\(^{-3}\) to 20 cm\(^{-3}\) (Figure 5.2, panel c) and the solar wind speed increases by a factor of 1.2 from 400 km s\(^{-1}\) to 475 km s\(^{-1}\) (Figure 5.2, panel d) resulting in the median solar wind dynamic pressure increasing from 2 nPa at \( t=0 \) to 7 nPa at \( t=+3 \) h (Figure 5.2, panel e; and Table 1). The median solar wind temperature is also enhanced after \( t=0 \) from 50 \( \times 10^3 \) K to 120 \( \times 10^3 \) K (Figure 5.2, panel f), falling to 75 \( \times 10^3 \) K, near its prestorm value, after \( t=+15 \) h. The temperature also, however, remains significantly different from \( t=-48 \) h for the rest of the five day interval. The energy input, \( U(t) \), is highly skewed toward higher values both before and after \( t=0 \) with the upper quartile rising from 2 \( \times 10^{12} \) W to 6 \( \times 10^{12} \) W within 1 h of the storm onset (Figure 5.2, panel g).

The median of all three magnetic indices, \( AL \), \( Kp \) and \( Dst \) also change rapidly at \( t=0 \). The median value of \( AL \) falls from \(-100 \) nT at \( t<0 \) to \(-200 \) nT at \( t=+1 \) h and \(-300 \) nT at \( t=+11 \) h (Figure 5.2, panel h), exhibiting a large skew in the distribution toward increased negative values, with the lower quartile reaching \(-500 \) nT at \( t=+8 \) h. The median \( Kp \) rises from 2 at \( t<0 \) to 5 at \( t=+3 \) h (Figure 5.2, panel i). The median value and the upper and lower quartiles of \( Dst \) rise sharply at \( t=0 \) from \(-20 \) nT to \(-5 \) nT.
(Figure 5.2, panel j), before falling smoothly with the median value, reaching −50 nT at t=+1.5 h.

Figure 5.3 presents a superposed epoch plot for class 1 SSCs (large) storms. For this class of storms the median $B_z$ does have an overall negative bias (Figure 5.3, panel a). The peak median $B_z$ (Figure 5.3, panel b) is more intense than for class 2 (small) SSCs (15 nT at $t=+4$ h, compared to 12 nT at $t=+1$ h for small SSCs). The median value of $B_z$ for both large and small SSCs becomes comparable at $t=+36$ h, with both traces converging for the remainder of the 5 days following the onset. The median solar wind density (Figure 5.3, panel c) however, peaks at a value similar to that for the class 2 SSCs, at about 20 cm$^{-3}$ at $t=+1$ h. The median solar wind speed (Figure 5.3, panel d) is significantly higher for large SSCs increasing by a factor of 1.4, from 400 km s$^{-1}$ to 575 km s$^{-1}$ compared with an increase by a factor 1.2 for small SSCs. The peak in the median value of solar wind pressure (Figure 5.3, panel e) is larger for large SSCs, peaking at 8 nPa, with the upper quartile reaching 12 nPa (7 nPa and 10 nPa respectively for small SSCs). The median solar wind temperature is also enhanced, reaching 200 x $10^3$ K at $t=+2$ h, falling rapidly to 60 x $10^3$ K by $t=+1.5$ h. The peak median value of $U(t)$ for large SSCs is a factor 1.3 greater than small SSCs ($3 \times 10^{12}$ W compared to $2 \times 10^{12}$ W). The distribution is, however strongly skewed toward high $U(t)$, with the upper quartile in excess of $9 \times 10^{12}$ W. $U(t)$ is sensitive to the solar wind speed, the IMF magnitude and the angle between the IMF and the Z direction ($\theta$). The first two components have been demonstrated to be, on average, higher during the more intense storms.

All three magnetic indices are enhanced for longer intervals for large storms, with $AL$ (Figure 5.3, panel h) remaining highly disturbed for 36 h (compared to 18 h for small SSCs [Figure 5.2, panel h]), and at a more intense level than for small SSCs, reaching a minimum of −400 nT compared to −300 nT for small SSCs. Median values of $Kp$ and $Dst$ (Figure 5.3, panels i and j respectively) undergo much smoother returns to prestorm values, but have higher peaks in activity (6− and −100 nT compared to 5− and −50 nT for small SSCs). Significance tests demonstrate that the mean $Kp$ was significantly different from its prestorm value until $t=+58$ h. However, the duration of
Figure 5.3  As for Figure 5.2 but for all large SSCs (see text for details).
enhancements in $B_z$ and $P_{sw}$ are less for the more intense class of storm ($t=31$ h compared to $t=36$ h for $B_z$ and $t=17$ h compared to $t=20$ h for $P_{sw}$).

### 5.3.3 Storm Gradual Commencements (SGCs)

Figure 5.4 presents a superposed epoch plot for the 202 class 2 (small) SGCs. This is the most abundant class of storm, containing marginally more storms than similar intensity SSCs. As with the average of all storms, the median $B_z$ (Figure 5.4, panel a) has an overall negative bias for 24 h after the onset, reaching a peak in activity of $-4$ nT at $t=+8$ h (compared to $-2$ nT at $t=+4$ h for the average of all storms). For approximately 75% of the 202 events, the IMF $B_z$ component is negative during this 24 h period. The median $B_z$ is significantly different from the $t=-48$ h after $t=-2$ h. (Figure 5.4, panel b; timings summarised in Table 5.1) and rises smoothly before peaking at 9 nT at $t=+5$ h (compared to 12 nT for the average of all storms). Median $B_z$ then smoothly falls and ceases to be significantly different from $t=-48$ h at $t=+29$ h. There is also an increase in the median solar wind density (Figure 5.4, panel c), but this is small (8 cm$^{-3}$ at $t=-12$ h to 13 cm$^{-3}$ at $t=+4$ h) and gradual. The median density then smoothly falls to a stable value of 7 cm$^{-3}$ by $t=24$ h. The median solar wind pressure (Figure 5.4, panel e) rises smoothly from 2 nPa to 4 nPa by $t=+8$ h, before smoothly falling, ceasing to be significantly different from its prestorm value at $t=+26$ h. The median solar wind temperature remains relatively unchanged directly after $t=0$, rises from $50 \times 10^3$ K to $125 \times 10^3$ K between $t=+6$ h to $t=+10$ h, remaining at a value greater than $100 \times 10^3$ K until after $t=+48$ h (Figure 5.4, panel f). Median $U(t)$ (Figure 5.3, panel g) rises slowly reaching a peak value at $3 \times 10^{12}$ W at $t=+12$ h.

The median values of all three magnetic indices (panels h, i and j) are subject to a relatively smooth increase in activity from $t=0$, with peak activity of of $-350$ nT, 5 and $-50$ nT for $AL$, $Kp$, and $Dst$ respectively at $t=+9$ h for $AL$ and $Kp$ and 14 h for $Dst$. There was no positive rise in $Dst$ at $t=0$ for SGCs. Mean values of $Kp$ and $Dst$ remained significantly different from their prestorm value until $t=+53$ h, and $t=+76$ h respectively. The rapid change in the median and quartiles of $AL$ and $Dst$ at $t=0$ suggest that any errors resulting from incorrectly defining the onset time of SGCs, as discussed in Section 5.2,
Figure 5.4 As for Figure 5.2 but for all small SGCs (see text for details).
have minimal effect.

There were only 25 SGC events for which Dst fell below -100 nT for four consecutive hours, generating ~13 data points per hour, insufficient to draw any reliable conclusions.

5.4 Discussion

5.4.1 Comparison of SSC and SGC events

This discussion begins with a comparison of the two types of storm, SSCs and SGCs, by considering the changes in the solar wind which may be responsible for the increased energy input. Superposed epoch plots of the mean value of $U(t)$ (rather than the median value shown) reveal that the mean energy input into the magnetosphere from the solar wind is approximately the same for class 2 (small) SSCs and SGCs ($=3.5 \times 10^{17}$ J during the first 24 h after $t=0$), implying that although the mechanism through which the energy is injected into the magnetosphere may be different, the total energy transferred is the same.

For small SSCs there is no overall bias in the sign of the IMF $B_z$ component (Figure 5.2a) whereas for comparable SGCs there is a negative bias in $B_z$ for 24 h after the storm onset, with the median peaking at $-4$ nT (Figure 5.4, panel a). The IMF magnitude, $B_n$, is more enhanced during small SSCs (12 nT, compared with 9 nT for small SGCs) with the SSC distribution exhibiting a larger spread of data points after $t=0$ for both $B_z$ and $B_n$. During small SSCs, the difference between the upper and lower quartiles for the $B_z$ component is 8 nT, compared with 4 nT for SGCs, and the difference for $B_l$ is 6 nT, compared with 4 nT for SGCs. This then implies that sustained intervals of reconnection occur during the SGC events, whereas enhanced, although possibly short lived, intervals of reconnection occur during SSC events.

The solar wind pressure is considerably enhanced after $t=0$ for SSCs (increasing from 2 nPa to 8 nPa), compared to a more gentle rise for SGCs (2 nPa to 4 nPa). Figure 5.5a illustrates schematically solar wind parameters of the superposed epoch trace for an SSC. There is a simultaneous sharp increase in density and speed, with evidence of a second rise in density at $t=6$ h. At $t=0$ there is also a sharp increase in ion temperature before falling to near its pre-storm value by $t=+15$ h. This is similar to the
Figure 5.5  Schematic illustration of solar wind speed, density and pressure for:  
(a) superposed epoch plot of an SSC;  
(b) a typical CME [e.g. Burlaga, 1991];  
(c) superposed epoch plot of an SGC;  
(d) high speed/ slow speed stream interface [e.g. Burlaga, 1974; Gosling et al., 1978].  
This Figure illustrates the similarities between SSC and CME signatures and the similarities between SGC and high speed/ slow speed stream interface signatures.
characteristic signature of the passage of a shocked coronal mass ejection (CME) illustrated in Figure 5.5b [e.g. Burlaga, 1991]. For SGCs (illustrated in Figure 5.5c) there is a smaller increase in density peaking at \( t=+4 \) (Figure 5.4c), and a much slower increase in the solar wind speed (and IMF magnitude), peaking at \( t=+24 \) h after the density has returned to its prestorm value. There is a delay in the increase in the solar wind temperature of 6 h, which only slowly decreases and falls to near its prestorm value after \( t=+48 \) h. This is similar to the characteristics of the solar wind during the passage of a high speed/low speed stream interaction [Burlaga, 1974] illustrated in Figure 5.5d. This suggests that the majority of SSCs are caused by CMEs, where as SGCs are usually the result of high speed/low speed stream interactions. Since SSCs comprise 85% of the class 1 (large) storms, it is inferred from these results that the majority of large storms (\( Dst<-100 \) nT for four consecutive hours) are a result of the passage of a shocked CME. This is in agreement with the work of Gosling et al. [1991].

Moving now to the magnetospheric response, the AL index for small SGC events has a peak median value of \(-350\) nT and remains below \(-200\) nT from \( t=0 \) to \( t=36 \) h (Figure 5.4h). For small SSCs the peak median activity is \(-300\) nT and remains below \(-200\) nT from \( t=4 \) h to \( t=16 \) h, approximately 33% of the time for small SGCs. Thus more persistent high latitude magnetic activity, probably substorm activity, is present during small SGCs than for similar intensity SSCs.

The peak in the median value of both \( Kp \) and \( Dst \) is the same for both types of storms, at values of 5– for \( Kp \) (Figures 2i and 4i) and \(-50\) nT for \( Dst \) (Figures 2j and 4j), although the rise in activity is steeper for SSCs, with \( Dst \) (median values and quartiles) exhibiting a positive rise at \( t=0 \), which is not present in the case of SGCs. This is supportive of the above inference that SSCs are associated with CMEs, with a clearly defined shock striking the magnetosphere at \( t=0 \). For SGCs there is no evidence of a shock, implying that for the SGCs, initial activity is a result of enhanced reconnection, probably a result of downstream compression of the IMF by the high speed solar wind stream.

### 5.4.2 Comparison of Small Storms with Large Storms

Unlike class 2 (small) SSCs, class 1 (large) SSCs have an overall bias in the \( B_z \) component (Figure 5.3a), with a median value of \(-4\) nT, and between 50% and 75% of
the distribution of $B_z$ is negative for the first 24 h of the storm. The median value of $B_z$ is similar to class 2 SGCs (Figure 5.4a), although with a larger spread of the distribution. The field magnitude is more enhanced for large SSCs, with the median value 15 nT, approximately 50% greater than for small SSCs (Figure 5.2b) and SGCs (Figure 5.4b). This suggests that both sustained, and more enhanced reconnection are important in the generation of larger magnetic storms. Furthermore, comparison of $Kp$ to its prestorm values reveal that large SSCs take longer to recover than small SSCs (58 h, compared with 41 h for small SSCs; see Table 5.1), but both $B_z$ and $P_{sw}$ return to their prestorm values more rapidly (31 h and 17 h for $B_z$ and $P_{sw}$ respectively, compared with 36 h and 20 h for small SSCs). This implies that energy is injected at a faster rate for the larger storms.

The distribution of the values of $U(t)$ during large and small SSCs are very similar (Figures 5.3c and 5.2c respectively), with a peak median value of 20 cm$^{-1}$ and the upper quartile reaching 30 cm$^{-1}$. However, in the case of the large SSCs the solar wind speed is more enhanced, with a peak median value of 575 km s$^{-1}$ (compared with 475 km s$^{-1}$ for small SSCs; Figure 5.2d). This is consistent with the generation of a larger magnitude IMF since it is the speed difference between the downstream solar wind and shock front/high speed stream which is responsible for compressing the magnetic field and is in agreement with Phillips et al. [1993].

The peak median value of $U(t)$ for class 1 (large) SSCs is factor 1.5 greater than class 2 (small) SSCs ($3 \times 10^{12}$ W compared to $2 \times 10^{12}$ W; Figure 5.3 and 5.2). The distribution is, however, strongly skewed toward high $U(t)$, with the upper quartile in excess of $9 \times 10^{12}$ W for large SSCs (mean $U(t)$ (not shown) is a factor of 2 greater for large SSCs than for small SSCs). $U(t)$ is defined by Equation 5.1 and is sensitive to the solar wind speed, the IMF magnitude and the angle between the IMF and the Z direction, $\theta$. The first two components have been demonstrated to be, on average, higher for more intense storms. This result simply illustrates that more energy is injected into the magnetosphere during a large magnetic storm.

All three magnetic indices are more disturbed for the large SSCs, with median $Dst$ peaking in activity at $-100$ nT (Figure 5.3j), twice that for the smaller SSCs (Figure 5.2j). However, the time between the onset to the peak activity is 11 h for both
classes. $K_p$ peaks at 6 for large SSCs (Figure 5.2i), larger than the median value of 5–for small SSCs (Figure 5.3i), with the median peak activity occurring 9 h and 3 h after the onset for large and small SSCs respectively. The recovery time is also longer for larger storms (58 h for $K_p$ to recover for class 1 SSC, compared to 41 h for class 2 SSCs).

The median $AL$ index for class 1 SSCs and class 2 SGCs is similar, with both remaining less than ~200 nT for ~36 h (compared with 12 h for class 2 SSCs; Figure 5.2h). This indicates that the additional enhancement in $Dst$ and $K_p$ for the larger SSCs compared to small SGCs is not due to tailside particle injection during the substorm expansion phase, but possibly resulting from particle injection associated with enhanced convection [see e.g. Gonzalez et al., 1994; Lui, 1994; Iyemori, 1994]. This is in agreement with Kamide (1992) who concluded that a substorm was not a necessary condition for a magnetic storm, but that the IMF conditions required for a magnetic storm also meet the requirements for producing a substorm. It may simply be, however, that the substorm expansion phases during SGCs may be less efficient at injecting particles into the symmetric ring current than during SSCs [e.g. Gonzalez et al., 1994].

The time between onset and peak in activity in the $AL$ index is approximately the same, within 2 h, for each class of storm with class 1 and 2 SSC and class 2 SGC peaking at 11 h, 11 h and 9 h respectively (see Table 5.1).

Table 5.2, first three rows, summarises the controlling parameters of both SGCs and SSCs. Small SSCs are initiated by the transfer of energy to the magnetosphere by the impulse of a shock in the solar wind and then driven by relatively short periods of enhanced reconnection. Small SGCs are driven by periods of sustained, although not necessarily enhanced, reconnection with the solar wind characteristics similar to the signature of a high speed/low speed stream interaction. However, large SSCs are driven by sustained periods of enhanced reconnection. Furthermore, since SSCs (both class 1 and 2) have solar wind characteristics of CMEs and most large storms are SSCs it is inferred that large storms are primarily caused by CME events.

### 5.4.3 Effect of $B_z$ Directly After the Onset

The purpose of separating out storms by the sign of $B_z$ directly after the onset is to attempt to isolate storms where dayside reconnection occurred at the onset, and those for
<table>
<thead>
<tr>
<th>Type of storm</th>
<th>Associated solar wind parameters</th>
<th>Approximate energy transferred (in first 24 hours) ((J))</th>
<th>Duration of perturbation of parameters (hours)</th>
<th>Delay from onset to max perturbation (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SGC Class 2</td>
<td>(B_z)</td>
<td>(3.5 \times 10^{17})</td>
<td>29</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>26</td>
<td>9</td>
</tr>
<tr>
<td>SSC Class 2</td>
<td>Solar wind density</td>
<td>(3.5 \times 10^{17})</td>
<td>36</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>20</td>
<td>11</td>
</tr>
<tr>
<td>SSC Class 1</td>
<td>Solar wind velocity (B_z)</td>
<td>(1.0 \times 10^{18})</td>
<td>31</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>17</td>
<td>11</td>
</tr>
<tr>
<td>Bz North</td>
<td></td>
<td>(5.0 \times 10^{17})</td>
<td>29</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>17</td>
<td>10</td>
</tr>
<tr>
<td>Bz South</td>
<td></td>
<td>(5.0 \times 10^{17})</td>
<td>34</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>20</td>
<td>1</td>
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</table>

Table 5.2  Summary table presenting controlling parameter for SSCs (class 1 and 2), SGCs (class 2 only), and storms for which \(B_z\) were positive and negative directly after the onset. Also included in this table is the mean energy transferred into the magnetosphere from the solar wind during the first 24 h after \(t=0\), the times from the onset that \(B_t\), \(P_{sw}\) and \(Kp\) are significantly different from \(t=-48\) h values, and the time between storm onset and the peak in activity for \(AL\), \(Kp\) and \(Dst\).
which some other factor must have been responsible for the start of the storm. Figure 5.6 presents superposed epoch plots of the median and upper and lower quartiles for various parameters for all storms for which $B_z$ was negative at $t=+1$ h. Also shown is the mean and standard errors for the IMF $B_z$ component (Figure 5.6, panel a). There is a strong $B_z$ negative bias in both the mean and median ($<-4$ nT; Figure 5.6, panels a and b respectively) directly after $t=0$, again taking 24 h before returning to near zero. However, prior to the onset the mean $B_z$ also has a small but negative bias (1 nT) for ~12 h. The median of $B_z$ is also negative prior to the onset but is only ~0.5 nT, with the upper and lower quartiles at 1.5 nT and ~3 nT.

For $B_z$ positive at $t=+1$ h (Figure 5.7), the mean and median values of $B_z$ (Figure 5.7, panel a and b) remain positive for 8 h, peaking at +5 nT within 2 h of the onset. After becoming negative, the median value of $B_z$ remains negative until $t=+24$ h (with a mean magnitude ~2 nT). As with the $B_z$ negative case (Figure 5.6) there is a bias in the mean and median for ~12 h preceding the onset, but in this case the bias is positive (Figure 5.7, panel a and b).

All three magnetic indices exhibit a delay for $B_z$ positive, with the effect being most noticeable in $A_L$ (Figure 5.7, panel i), which falls from ~100 nT to ~300 nT at $t=+8$ h. $Kp$ (panel i) also peaks at $t=+8$ h, having risen rapidly at $t=0$ and levelled off. $Dst$ (Figure 5.7, panel j) is less negative in the case of $B_z>0$ prior to the onset, falling to 0 nT soon after $t=0$. $Dst$ then falls smoothly, reaching its prestorm value at $t=+8$ h, and peaking in activity at $t=+18$ h. Thus in the case of $B_z$ positive, all three output parameters have a double response, with the first probably being in response to the step function in the solar wind dynamic pressure (Figure 5.7, panel f), although in the case of $A_L$ the initial increase in magnetic activity may have been due to a northward turning in $B_z$ acting as a trigger of the substorm expansion phase onset [e.g. Rostoker et al., 1983]. The second change in the output parameters are probably in response to the enhanced southward turning of the IMF and subsequent increase in the magnetospheric energy input $U(t)$.

Significance tests indicate that if $B_z$ is positive directly after the onset, the recovery time for $Kp$ is 72 h compared to 41 h for the case of $B_z$ negative, with all three magnetic indices less disturbed than for $B_z$ negative prior to the onset (e.g. the median value of $Dst=+20$ nT for $B_z<0$, compared to $Dst=-15$ nT for $B_z>0$). However, after 24 h the
Figure 5.6 As for Figure 5.2 but for all storms for which it has been identified that $B_z$ was negative directly after the onset: a) IMF $B_z$ (mean and standard errors); b) IMF $B^z$ (median and quartiles; also displayed in subsequent panels); c) IMF $B_t$; d) solar wind density; e) solar wind speed; f) solar wind dynamic pressure; g) solar wind temperature; h) Rate of energy input into the magnetosphere; i) $U(t)$; j) $AL$; k) $KP$; k) $Dst$. 
Figure 5.7 As for Figure 5.6 but for all storms for which $B_z$ was identified to be positive directly after the onset.
magnetic indices for both $B_z$ positive and $B_z$ negative converge. This apparent discrepancy may be explained by studying $Dst$ prior to the onset. For $B_z$ positive, the median and upper and lower quartiles are at a less negative value ($-10$ nT for the median, compared to $-20$ nT for $B_z$ negative). Thus for the case of $B_z$ positive, the magnetic indices are less active, although the level to which they recover is the same as the activity prior to storms for which $B_z$ was negative directly after the onset. This implies that on average less energy is coupled from the solar wind into the magnetosphere prior to the onset, supporting the finding that the sign of $B_z$ directly after the onset is the dominant sign prior to the onset. The solar wind and IMF return to their prestorm values quicker for $B_z^>0$ implying that the rate of energy injection is faster for the case of $B_z$ positive directly after the onset. However, the mean (rather than the median) energy input over the first 24 h following the onset is the same for both $B_z$ positive and negative (Table 5.2, last two rows).

The time between the onset and peak in activity for all three magnetic indices is greater for $B_z$ positive (10 h, 7 h and 20 h for $AL$, $Kp$ and $Dst$ respectively; compared with 1 h, 4 h and 10 h for $B_z$ negative). For $B_z$ positive, the solar wind input parameters return to their prestorm values earlier, but the peak in magnetic activity occurs later than for $B_z^<0$. It is implied that the energy is, therefore, injected into the magnetosphere at a quicker rate for $B_z$ negative. This is supported by a higher peak in the upper quartile of $U(t)$ of $42 \times 10^{12}$ W at $t=+13$ h compared with $36 \times 10^{12}$ W at $t=+4$ h for $B_z$ negative. However it must also be noted that there is an enhancement in the upper quartile of $U(t)$ between $t=-48$ h and $t=-24$ h, which does not have an apparent effect in the magnetospheric response as measured by the magnetic indices employed.

5.5 Summary

In this study, geomagnetic storms have been classified according to their intensity and whether the storm began with a sudden or gradual commencement. On the time scales investigated, of the order of the magnetic storm time scale itself, both the solar wind and IMF changes are responsible for generating the storms, with the geomagnetic response occurring almost simultaneously with these changes, to within the resolution of the data.

Sustained intervals of southward IMF are the controlling parameter for small
SGCs, whereas it is the solar wind density which is the distinguishing parameter for small SSCs. Large SSCs arise from intervals of sustained and enhanced IMF resulting from high solar wind velocities. The superposed epoch signature of solar wind plasma for SSCs is similar to the signature of a CME, whereas the superposed epoch signature of a SGC is characteristic of the passage of a high/low speed coronal stream interface. These results suggest that CMEs are largely responsible for SSCs but a high speed/low speed stream interaction is more likely to generate an SGC. Since SSCs comprise ~85% of large storm, it is inferred that shocked CMEs are responsible for the majority of large magnetic storms ($Dst < -100$ nT for four consecutive hours).

The superposed epoch signatures of $AL$ are similar for small SGCs and large SSCs, both at enhanced activity compared with small SSCs. It is suggested that enhancements in $Kp$ and $Dst$ for large SSCs compared to small SGCs is due to particle injection associated with the convection electric field. The inference is that a magnetic storm is not necessarily the sum of a succession of magnetospheric substorms. The interval between storm onset and time-to-peak activity is independent of the type of onset (gradual or sudden) and of the intensity of the storm. Storms driven by sustained reconnection recover more slowly, even though the enhancements in the solar wind and IMF return to their prestorm values earlier.

The sign of $B_z$ directly after the onset is the prevailing sign for 12 h to 24 h prior to the storm. If $B_z$ is positive (northward) directly after the onset, activity is slow to develop and is dependent upon a rapid injection of energy once $B_z$ has turned negative. Both the recovery time and time-to-peak activity of the geomagnetic response is greater for $B_z$ positive, although the solar wind dynamic pressure and IMF magnitude return to prestorm values earlier.
CHAPTER 6

Universal Time and Seasonal Variations in the Occurrence of Geomagnetic Storms

6.1 Introduction

In this chapter, a study of the seasonal and UT variations in magnetic storm occurrence based upon the data set employed in Chapter 5 is undertaken. The following three sections discuss the seasonal variation in occurrence of SGCs and SSCs and UT variations in the onset times and peak activity of SSCs and SGCs for both season-dependent and season-independent activity. Each of these sections starts with a short paragraph summarising the predictions of the various models (discussed in Section 2.4) and analytical techniques employed. This is then followed by a description and discussion of the results.

6.2 Seasonal Variations in the Occurrence of SSCs and SGCs

6.2.1 Predictions and Analytical Techniques

For all three types of variation investigated in this chapter (the semi-annual variation presented in this section and season-dependent and season-independent UT variations discussed in Sections 6.3 and 6.4), the observed and model behaviour are compared by means of statistical tests. It is not possible, using these tests, to conclude that the observed distribution is correctly described by the model, although it may be possible to confidently rule out the model as the correct mechanism of the observed variation. In general in this chapter, the 95% confidence level (1 in 20) is adopted as a boundary between distributions which are consistent with the model and those which are not.

There are three main models which predict seasonal variations in geomagnetic activity. The heliospheric latitude model predicts maximum magnetic activity when the Earth is at extremes of solar latitude on 5 March and 6 September [Section 2.4.1]. The McIntosh effect [Section 2.4.2] predicts maximum activity when the Earth dipole is, on
average over 24 h, least inclined to the Earth-Sun line, which will occur at the equinoxes on 21 March (day 80) and 21 September (day 264). The Russell and McPherron effect, based on the projection of $B_y$ (GSE) into $B_y$ (GSM), predicts maxima on 5 April (day 95) and 5 October (day 278) [Section 2.4.3].

6.2.2 Observations
Figures 6.1a and 6.1b present the seasonal variation of all SGCs and all SSCs respectively between 1963 and 1991. The storms have been divided into monthly bins. For SGCs (Figure 6.1a) there are peaks in occurrence in April and October and minima in January and July. The equinoctial amplitudes are $\sim 30$ events, compared to 6 in July and 10 in January. A $\chi^2$ test comparing the observed distribution to a straight line gives a confidence level of greater than 99.99%, indicating that it is very unlikely that such a distribution is uniform.

The seasonal distribution of SSCs (Figure 6.1b) exhibits little evidence of semi-annual variation. There is still a peak in April and evidence of a peak in September, but the minima occur in August and November. The ratio between maximum (in April) and minimum (in August) is $\sim 3:2$. Furthermore, using the $\chi^2$ test to compare the observed distribution to that of a uniform distribution gives a confidence level of 27.4%. The observed variation in the seasonal occurrence of SSCs is therefore indistinguishable from a uniform distribution.

6.2.3 Discussion
There is a strong semi-annual variation observed in the occurrence statistics of SGCs. The peaks occur in the months following the peaks previously observed in geomagnetic activity [A. S. Rodger, private communications, 1994] and predicted by the models. The ratio of the maximum and minimum is between of 3:1 and 5:1. If SSC and SGC events are considered together the ratio falls to $\sim 2:1$. This result is consistent with the conclusions in Section 5.4.1 that different solar wind phenomena are responsible for SSCs and SGCs. SSCs are primarily the result of the impact on the magnetosphere of coronal mass ejections and are associated with enhanced solar wind dynamic pressure (in particular the solar wind velocity), whereas SGCs are driven by enhanced and sustained
Figure 6.1 Monthly distribution of magnetic storm occurrence statistics for a) SGC events only and b) SSC events only (all SSCs - light shading; large SSCs - dark shading). See text for further details.
intervals of southward IMF, compressed by a high speed/low speed stream interface. The results presented in Figure 6.1 and the results of Berthelier et al. [1976], Russell [1989] and Chapter 5 are all consistent. The southward component of the IMF compressed by high speed/low speed stream interactions is strongly modulated by the Russell and McPherron effect, resulting in a strong seasonal dependence in the occurrence of SGCs. A CME, on the other hand, will strike the Earth's magnetosphere regardless of the orientation of the Earth's dipole axis and hence result in a magnetic storm regardless of season. As indicated in Chapter 5, the intensity of an SSC is also governed by the intensity and duration of negative $B_z$, with large SSCs, associated with large and sustained intervals of southward IMF. If those SSCs when $Dst \leq -200$ nT for at least four consecutive hours are considered (Figure 6.1b, dark shading) there is evidence of a semi-annual variation. The number of events, however, is small although the resulting $\chi^2$ value of 88.5% does suggest the existence of a semi-annual variation. The results presented above demonstrate that the solar wind does not play a leading role in the modulation of the semi-annual variation in the occurrence of magnetic storms and hence the heliospheric latitude model of seasonal magnetic activity is ineffective in modulating the observed activity.

6.3 Season-Independent UT Variations in Magnetic Storm Statistics

6.3.1 Predictions and Analytical Techniques

To study UT variations of magnetic storms, onset times and the times of peak activity in both $Am$ and $Dst$ have been divided into 3 h bins. The results presented in this chapter exclude the events 10 days either side of the equinoxes so that a direct comparison can be made with the "winter minus summer" distributions discussed in Section 6.4 with the total number of events in each 3 h UT bin discussed here. The removal of the storms near equinoxes for study of the UT variations (Sections 6.3 and 6.4) leaves about 90% of the original number of onsets.

Both the McIntosh effect and the Russell and McPherron effect described in Sections 2.4.2 and 2.4.3 predict UT variations in geomagnetic activity. The Russell and
McPherron effect is dependent on the sign of $B_y$, which is on average zero. For $B_y$ positive, a peak is predicted at 1030 UT for all seasons, with the largest diurnal UT amplitude in September and the weakest in June. For $B_y$ negative the peak activity is predicted at 2230 UT, with the largest diurnal UT amplitude observed in March. By separating magnetic activity according to the sign of $B_y$, a peak has been observed at 1030 UT for positive $B_y$ and 2230 UT for negative $B_y$ for all seasons (Berthelier, 1976, Russell, 1989). No UT variation has been observed in magnetic activity for all $B_y$. A season-independent UT variation in magnetic activity modulated by the McIntosh effect would be manifest as twin peaks near 1030 UT and 2230 UT. Figure 6.2, top panel, illustrates the phase of the season-independent UT variation predicted by the McIntosh effect ($\sin^2 \psi$).

6.3.2 Observations

Figure 6.3 presents histograms of the number of storm onsets in each 3 h UT bin for all storm onsets, with the exception of storm onsets within 10 days of the equinoxes. Table 6.1 summarises the results of a $\chi^2$ confidence test comparing the observed distributions of Figures 6.3 and 6.5 with uniform distributions. The UT distribution of all storms (Figure 6.3a) is not significantly different from a uniform distribution at a $\chi^2$ confidence level of 78.8%. There are, however, more storm onsets between 0000 UT and 1200 UT than between 1200 UT to 2400 UT (260 to 200; Figure 6.3a). There is little evidence of any UT variation in the onset times of SSCs (Figure 6.3b), with a $\chi^2$ test giving a confidence level of only 16.7% when comparing the observed distribution with a uniform distribution. For SGCs, however, approximately twice as many storm onsets occur between 0000 UT and 1200 UT as occur between 1200 UT to 2400 UT (115 to 67; Figure 6.3c), with the peak occurring in the 0300 UT to 0600 UT bin. The result of a $\chi^2$ test to a straight line gives a confidence level of 98.97% that the distribution is non-uniform. In addition to the diurnal UT variation, there is evidence for a semi-diurnal UT variation with a weak secondary peak apparent in the SGC distribution in the 1800 UT to 2100 UT bin.

Figure 6.4 presents histograms of the UT distributions of the times of peak activity
Figure 6.2 Model universal time variation of the magnetic activity due to the McIntosh effect ($\sin^2\psi$) averaged over a year (top panel), and the average of northern winter months minus northern summer months $[(\sin^2\psi)_w - (\sin^2\psi)_s]$; bottom panel.
Figure 6.3 Histogram of the UT distribution of the onset time for a) SSCs and SGCs; b) SSCs and; c) SGCs. The distributions contain all storms except those which occurred 10 days either side of the equinoxes for comparison with Figure 6.8.
Confidence non-uniform Distribution (%)

<table>
<thead>
<tr>
<th></th>
<th>Confidence non-uniform Distribution (%)</th>
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</thead>
<tbody>
<tr>
<td>SC (Onset)</td>
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</tr>
<tr>
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<td>16.70</td>
</tr>
<tr>
<td>SGC (Onset)</td>
<td>98.97</td>
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<td>99.07</td>
</tr>
<tr>
<td>SGC (Peak Dst)</td>
<td>99.96</td>
</tr>
</tbody>
</table>

Table 6.1 Table presenting the results of a $\chi^2$ confidence test comparing the observed season-independent distributions of Figures 6.3 and 6.5 to uniform distributions.
Figure 6.4 Histogram of the UT distribution of the time of peak $Am$ for a) SSCs and SGCs; b) SSCs and; c) SGCs. The distribution contains all storms except those which occurred 10 days either side of the equinoxes for comparison with Figure 6.9.
of the Am index during the storms with the same equinoctial days excluded as for Figure 6.3. The presentation is the same as Figure 6.3, i.e. all storms panel a, SSCs panel b and SGCs panel c. There are fewer events presented in Figure 6.4 than Figure 6.3 since the Am index is not available for the whole of the interval covered in Figure 6.3. There is a clear anomaly when considering the number of storms in the distribution of all storms, SSCs and SGCs (Figure 6.4 a, b, c respectively), since only 4 events occur in the 0000 UT to 0300 UT bin, whereas in excess of 80 events occur in the adjacent 2100 UT to 2400 UT bin and 60 events in the 0300 UT to 0600 UT bin. Both Mayaud [1980] and Russell [1989] observed anomalously high values of mean Am in the 2100 UT to 2400 UT bin when studying the UT variation of the Am index. Figure 6.4 indicates that there is a limitation with the Am index around 0000 UT to 0300 UT during particularly disturbed intervals. It is therefore unsafe to draw any conclusions from the season-independent distribution.

Figure 6.5 presents the histograms of the UT variation of the time of the peak in Dst index during magnetic storms. The distribution for all storms (Figure 6.5a) exhibits a strong UT variation, with peaks in the 0600 UT to 0900 UT and 2100 UT to 2400 UT bins. In each peak there were ~75 events compared with only 25 events in the 1200 UT to 1500 UT bin. Comparing the observed distribution with a uniform distribution results in a confidence level of greater than 99.99% that the observed distribution is non-uniform. Considering SSCs and SGCs separately (Figures 6.5 b and c respectively), similar UT variations are evident in both classes of storms although SGCs have a larger number of events in the 0000 UT to 0300 UT bin. Although the results of the $\chi^2$ confidence test are greater than 99.0% for both SGCs and SSCs (99.96% and 99.07% respectively), the observed variation is more pronounced for SGCs, with the ratio between maximum and minimum of ~7:1, compared with ~2:1 for SSCs.

6.3.3 Discussion

Before discussing these results with respect to the theoretical prediction it is necessary to consider the impact of instrumentation effects on the validity of the onset times and times of peak activity in Dst deduced for storms. There is little sign of diurnal UT activity observed in the start time of SSCs. This would be expected since the start time is
Figure 6.5  Histogram of the UT distribution of the peak in the time of peak $Dst$ for a) SSCs and SGCs; b) SSCs and: c) SGCs. The distributions contain all storms except those which occurred 10 days either side of the equinoxes for comparison with Figure 6.10.
determined by a shocked impact on the magnetosphere with the resulting disturbance occurring near-simultaneously at all local times. There is, however, evidence for two UT variations in the onset times of SGCs, a preferential number occurring in one 12 h interval as well as two peaks in the distribution. As stated in Section 5.2, the onset times of SGCs have been determined by at least two stations reporting synchronised storm onsets in the Principal Magnetic Storm section of “Solar Geophysical Data”, which lead to Disturbances of less than −50 nT for four consecutive hours. Two possible biases may be incorporated into the deduced onset times of an SGC: a) a bias in the local times of the reporting stations, which might lead to a season-independent bias in the onset times; and b) a bias in the latitudes of the reporting stations (in particular, in which hemisphere the stations are located), which might lead to a season-dependent bias. The latter bias is discussed further in Section 6.4.3.

To investigate the possible bias in local time, the distribution in MLT of all stations which have contributed to the identification of each SGC onset time has been computed (Figure 6.6). In total, approximately 1000 reported onsets have been utilised in determining the onset times of 230 SGCs. A peak in the distribution is present near midday (0900 MLT to 1200 MLT bin), with a secondary peak observed near midnight (2100 MLT to 2400 MLT bin). Corresponding minima are observed at early morning (0300 MLT to 0600 UT bin) and late afternoon (1800 MLT to 2100 MLT bin). The ratio between maximum and minimum is of order 2:1. Approximately 75% of the onsets were reported by stations situated between 20°S and 20°N. The MLT distribution of low latitude stations alone (-20°N ≤ latitude ≤ 20°N) is, however, similar to Figure 6.6.

Figure 6.7 is a histogram of the number of low latitude (≤ 20°) reporting stations as a function of MLT at 0000 UT presented in 3 h bins (upper time axis). The light shading indicates stations located in the northern hemisphere and the dark shading those located in the southern hemisphere. The reporting stations will be located near 1030 MLT, which is the peak local time of reported storm onsets (Figure 6.6), by the transformation UT = 10.5 - MLT and this value is also included in the figure (lower time axis). A peak of 7 observatories are located in the +0300 MLT to +0600 MLT bin (+0600 UT), with no low latitude reporting stations located between -0900 MLT and -0300 MLT (-0600 UT). This would result in a positive bias in the onset time of SGCs which would
Figure 6.6 Histogram presenting the number of onsets reported by contributing stations as a function magnetic local time which reported onsets employed for determining the onset times of SGC events utilised in this study (see text for details).
Figure 6.7 Histogram of the magnetic local time of low latitude (<20°) reporting stations at 0000 UT employed to determine the onset times of SGC events. Light shading indicates stations in the northern hemisphere and dark shading stations in the southern hemisphere. Also included is the universal time that each 3 h bin is located at 1030 MLT (lower time axis).
occur near 0600 UT and a negative bias between 1330 UT to 1930 UT. The observed season-independent distribution in SGC onset times (Figure 6.3c) is roughly in phase with the potential biases discussed above and cannot be ruled out as the cause of the observed diurnal variation. Four stations, however, lie in the −1200 MLT to −0900 MLT bin (~2100 UT) and 2 stations in the −0300 MLT to 0000 MLT bin (~1200 UT) which are the minima in the distribution of onset times of SGCs in Figure 6.3c. Thus, although the diurnal UT variation may, at least in part, result from asymmetries in the local time of reporting stations, the potential bias due to the longitudinal distribution of stations is not entirely consistent with the observed semi-diurnal UT variation in the onset times of SGCs.

Mayaud [1980] discussed the validity of observed UT variations in the $D_{st}$ magnetic index, pointing out a minimum in the $D_{st}$ UT distribution (minimum $D_{st}$ is referred to as the least negative value) and hence a minimum in the ring current at ~1330 UT. $D_{st}$ is constructed from the $H$ component recorded by four low latitude magnetometer stations, three of which are in the northern hemisphere with the remaining station in the southern hemisphere. There is a large longitudinal gap between contributing stations HER and KAK of ~125°. Mayaud pointed out that at 1310 UT the centre of this gap is at the local time at which the partial ring current is most effective. Mayaud speculated that the observed UT variation in the $D_{st}$ index may result from the influence of the partial ring current on the longitudinal asymmetry of the contributing stations. The observed minimum in the UT distribution of the time at which peak $D_{st}$ occurs during SGCs is between 1200 UT and 1500 UT, consistent with the minimum in the UT variation of the $D_{st}$ index discussed above. Consideration must be given that part of the observed variation may be due to limitations of the $D_{st}$ index.

Moving now to a discussion of the results in accordance with the predictions of the various models. Figure 6.3b demonstrates that there is no evidence for season-independent UT variation in the onset times of SSCs. This is as expected since the onset times of SSCs are governed by the impact of a CME upon the magnetosphere, which is independent of the orientation of the Earth’s dipole axis. Figure 6.3c, on the other hand, demonstrates a season-independent component of UT variations in the onset times of SGCs at a confidence level of 99.0%. This variation in the onset time of SGCs appears to
contain two components; a diurnal UT variation, in which twice as many onsets occur between 0000 UT and 1200 UT than between 1200 UT and 2400 UT with a peak in the 0300 UT to 0600 UT bin and a semi-diurnal component, with a secondary peak in the 1800 UT to 2100 UT bin. It is not clear what may cause this season-dependent diurnal UT variation in the onset time of SGCs. It may, as already discussed, be a consequence of the longitudinal bias in the stations employed to generate the onset times. One other possibility may be longitudinal asymmetries in the geomagnetic field, although this is not confirmed with this data set. The semi-diurnal variation in onset times of SGCs, with peaks in the 0300 UT to 0600 UT and 1800 UT to 2100 UT bins, leads by 3 h to 6 h, the predicted season-independent peaks of the McIntosh effect (illustrated in Figure 6.2, top panel).

There is season-independent UT variation in the time of peak storm activity measured by $D_{st}$ (Figure 6.5), with peaks at 0600 UT to 0900 UT and 2100 UT to 2400 UT, in near agreement with the McIntosh effect. The peak $D_{st}$ distributions also mimic the UT variations of the $D_{st}$ index reported by Saroso et al. [1993]. In addition the observed minimum in the present study (1200 UT to 1500 UT) is also consistent with the minimum negative $D_{st}$ (and hence minimum ring current) discussed by Mayaud [1980] at ~1330 UT. The season-independent variation of peak activity of $D_{st}$ for SGCs is more pronounced than for SSCs and follows the UT variation of the $D_{st}$ index reported by Saroso et al. [1993] very closely, with a 1:1 correlation of rises and falls between the two distributions. Saroso et al. found that $dD_{st}/dt$ was anticorrelated with their calculations of the UT variations of the nightside oval magnetic flux threading the auroral oval. Saroso and co-workers suggested that as the magnetic field in the plasma sheet increases, the plasma drift velocity will decrease assuming the electric field remains constant, since $v_{E,B} = E/B$, thus reducing the plasma flow from the magnetotail. Although the UT peak of $D_{st}$ during SGCs is in agreement with the observations of Saroso et al., the electric field in the high latitude plasmasphere may not be constant during a substorm expansion phase and the cause of the UT modulation of the $D_{st}$ index is thus unclear.

Mayaud [1980] has suggested that the observed UT variations in the $D_{st}$ index may be artificial, resulting from the influence of the partial ring current on longitudinal asymmetries of the reporting stations. Chapter 5, in addition to demonstrating SGCs are
associated with longer intervals of sustained $B_z$ (and hence dayside reconnection) than
SSCs, also demonstrated that the $AL$ index was more disturbed during SGCs compared
to similar intensity SSCs (defined by $Dst$) [Section 5.4.1], inferring that more substorm
activity occurred during SGC events. Since the partial ring current is believed to be
generated by particle injection from the magnetotail [e.g. Nishida, 1978] this would result
in a more pronounced UT variation in the $Dst$ index during enhanced substorm activity
and hence a greater UT variation in peak $Dst$ during SGCs than SSCs, which is indeed
observed (Figure 6.5). The observed UT variation of the peak $Dst$ during magnetic
storms may therefore be, at least in part, artificial, resulting from limitations in the current
$Dst$ index.

6.4 Season-dependent UT Variations in Magnetic Storm Statistics

6.4.1 Predictions and Analytical Techniques

For studying season-dependent UT variations, onset times have again been divided into
3 h bins. Both the total number of storm onsets occurring in each 3 h bin and the
difference between the number of onsets in northern summer and the number of onsets in
northern winter were then calculated. Northern summer included all storms which
occurred between 31 March and 10 September and northern winter contained all storms
which occurred between 1 October and 10 March. Storms within 10 days either side of
the equinoxes have been excluded since the McIntosh effect predicts UT activity reversing
at the equinox. The advantage of calculating “winter minus summer” or “spring minus
autumn” is that season-dependent activity would be enhanced. Any season-independent
variations (either genuine magnetic variations or variations resulting from any
asymmetries in the longitudinal locations of reporting stations in “Solar and Geophysical
Data”) would cancel, although the resultant amplitude will vary. A two-tailed significance
test was undertaken on each 3 h UT bin to measure the confidence that the occurrence of
summer onsets to winter onsets was fair, based on a normal distribution [e.g. Spiegel,
1961].

The McIntosh effect predicts a diurnal distribution for northern “winter minus
summer” UT variation of geomagnetic activity as illustrated in Figure 6.2, bottom panel.
The predicted peak in the distribution occurs at 2239 UT and the minimum at 0439 UT. The season-dependent variation predicted by the Russell and McPherron effect is more complicated and is dependent upon the sign of $B_y$. For $B_y$ positive the peak is predicted to occur at ~1030 UT, with the maximum amplitude in September, whereas for $B_y$ negative the minimum occurs at 1030 UT with a maximum amplitude in March. Therefore "September minus March" would produce a single peaked pattern with a peak at 1030 UT and a minimum at 2230 UT.

6.4.2 Observations

Figure 6.8 presents the difference in the number of storm onsets between northern winter and northern summer as a function of universal time. The number of storms in winter and summer have been normalised such that the number of events are evenly distributed between summer and winter. The "error bars" in each panel of Figure 6.8 centred on zero represent the difference between winter and summer occurrence which would be required to obtain a 95% confidence level that occurrence rates for the two seasons were unequal, calculated on the basis of a random two tailed test discussed in Section 6.4.1. When exceeding 95%, the individual measured confidence level of northern "winter minus summer" for each 3 h bin is included at the top of each column. The solid lines present the predicted diurnal distribution based upon the McIntosh effect. The phase of the model distribution has been chosen such that the $\chi^2$ value calculated was the minimum of the 8 possible distributions resulting from different phases.

Figure 6.8a presents the UT distribution for the onset times for all storms. There is evidence for a diurnal distribution, although the maximum (0900 UT to 1200 UT bin) and minimum (1800 UT to 2100 UT bin) are not 12 h out of phase. One bin, 1800 UT to 2100 UT, has a confidence level greater than 95% that the occurrence rate for the two seasons are unequal. Comparing the observed UT distribution to a uniform distribution results in a confidence level of 93.9%, whereas comparison to the predicted McIntosh season-dependent distribution (Figure 6.2, bottom panel) results in a confidence level of 40.9%, with the observed distribution leading the model distribution by 6 h.

For SSCs, there is less evidence of any season-dependent UT variation in onset time (Figure 6.8b), with the peak and minimum of the distribution in adjacent 3 h bins.
Figure 6.8  Histograms presenting the difference between northern winter and summer onset times of storms (bottom panel) as a function of UT. The "error bars" about zero in the northern "winter-summer" distributions represent the difference between winter and summer occurrence which would be required for 95% confidence that occurrence rates for the two seasons were fair, calculated from a random two sided test. The individual measured confidence levels of each 3 h bin ≥95% are included at the top of each column. The solid black lines present the model distribution based on the McIntosh Effect with phase such that the calculated $\chi^2$ between the two distributions is at a minimum: a) SSC + SGC events; b) SSC events only; and c) SGC events only. See text for further details.
The 1800 UT to 2100 UT bin is again the only bin where the difference between winter and summer was non-uniform at a confidence level of ≥95%. A $\chi^2$ test gives a confidence level of 85% when comparing the observed distribution as a whole to a uniform distribution and a confidence level of 56.9% is obtained when comparing it to a season-dependent McIntosh distribution with the observed distribution leading by 6 h. Figure 6.8c suggests that there is a diurnal UT variation in the onset times of SGCs; the maximum and minimum of the distributions are in the 0900 UT to 1200 UT and 2100 UT to 2400 UT bins respectively. A peak of +12 occurs in the 0900 UT to 1200 UT bin, with a total of 20 SGCs occurring in that bin (see Figure 6.3c). This gives a ratio of 4:1 of SGC events occurring in northern winter to that occurring in the same 3 h bin in northern summer, with a confidence level of 99.6% that the difference is non-uniform. A similar ratio is also observed in the 2100 UT to 2400 UT bin, although with only a total of 15 SGC events in that 3 h bin the confidence level is reduced to 92.8%. In addition a $\chi^2$ test gives a confidence level of 94.5% that the distribution as a whole is non-uniform and a confidence level of 68.4% when comparing to a McIntosh distribution, leading the McIntosh effect by 6 h. It is therefore unlikely that the observed distribution is uniform, but it is consistent with a diurnal distribution which leads the predictions of the McIntosh effect by 6 h. The difference between the UT distributions of storm onsets centred on the equinoxes for both SSC and SGC events has also been calculated (not shown). There was no evidence of any UT variation present in either class of storm.

Figure 6.9 presents the northern “winter minus summer” UT variation in the time of peak activity for the $A_m$ index during storms and is of the same format as Figure 6.8. A strong season-dependent UT variation is apparent in the time of peak $A_m$ during all storms (Figure 6.9a), with a minimum in the distribution in the 0600 UT to 0900 UT bin at a confidence level of 99.90% that the summer to winter difference is non-uniform. The peak in the distribution occurs in the 2100 UT to 2400 UT bin at a confidence level of 99.90% that the summer to winter difference is non-uniform. A $\chi^2$ test gives a confidence level of 73.5% when comparing the observed distribution to a McIntosh distribution and the observed distribution leads the McIntosh effect by 3 h. A confidence level of greater than 99.99% is inferred when comparing the distribution as a whole with a uniform distribution. The season-dependent distribution for the time of peak $A_m$ for SSCs is
Figure 6.9 As Figure 6.8, for except presenting UT variations in the peak activity of the Am index during magnetic storms for: a) SSC + SGC events, b) SSC events only; and c) SGC events only.
similar to that for all storms (Figure 6.9b). In this case, while the minimum occurs in the same UT bin, the peak in the distribution occurs in the 1800 UT to 2100 UT bin, which is in phase with the observed UT variation of the Am index itself [e.g. Mayaud, 1967, 1980; Berthelier, 1976, Russell, 1989]. Comparison with a McIntosh distribution results in a $\chi^2$ confidence level of 20.3% lagging the McIntosh effect by 3 h and a confidence level of greater than 99.99% that the distribution is non-uniform. There is less evidence for UT variations in the peak Am during SGCs (Figure 6.9c), with the only significant “winter minus summer” bin at 2100 UT to 2400 UT. A $\chi^2$ test gives a confidence level of 96.9% that the observed distribution is non-uniform and a confidence level of 85.4% when comparing the observed distribution to a McIntosh distribution, with a phase lag of 6 h. Although there are fewer SGCs than SSCs (158 SGCs compared with 213 SSCs), little difference is made to the SSC distribution presented if the number of SSC events is randomly reduced to equal SGCs.

Figure 6.10 presents the northern “winter minus summer” UT distributions of the time of the peak activity of the Dst index during storms and is of the same format as Figures 6.8 and 6.9. There is a strong season-dependent variation visible in the distribution for all storms (Figure 6.10a), with a peak in the 1500 UT to 1800 UT bin and a minimum in the 0300 UT to 0600 UT bin, at confidence levels of 98.4% and 98.8% respectively that the difference between winter and summer events are non-uniform. In addition a $\chi^2$ confidence test on the distribution as a whole gives a confidence level of 99.9% that the observed variation is non-uniform and 25.0% when comparing the observed distribution with a season-dependent McIntosh distribution and is in phase with the McIntosh effect. The diurnal UT variation is also present in SSC and SGC events considered separately (Figures 6.10b and 6.10c respectively), with both distributions at high confidence levels with comparison to a uniform distribution (97.7% and 99.1% respectively) and comparatively low confidence levels when compared to a McIntosh distribution (17.4% and 65.9% respectively, both with zero phase lag).

Table 6.2 contains a summary of these results. Classes of storms which have the maximum and minimum in the season-dependent variation separated by 12 h have been shaded and the phase lags with respect to the minimum confidence level $\chi^2$ McIntosh
Figure 6.10 As Figure 6.8, for except presenting UT variations in the peak activity of the $D_{st}$ index during magnetic storms for: a) SSC + SGC events, b) SSC events only; and c) SGC events only.
<table>
<thead>
<tr>
<th>McIntosh</th>
<th>Maximum (UT)</th>
<th>Minimum (UT)</th>
<th>Phase Lag ( \chi^2 ) McIntosh (h)</th>
<th>Confidence non-McIntosh distribution (%)</th>
<th>Confidence non-uniform distribution (%)</th>
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<td>SC (onset)</td>
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<td>18-21</td>
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<td>99.1</td>
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Table 6.2 Table presenting the results of \( \chi^2 \) confidence tests on the distributions in Figures 6.8 to 6.10. The table includes \( \chi^2 \) confidence levels comparing the observed distributions to uniform distributions and the season-dependent McIntosh distribution presented in Figure 6.2, lower panel. The table also includes the times at which maxima and minima in the observed distributions occur and gives the relative phase to the best fit model McIntosh distribution employed.
model distribution when compared to the McIntosh effect are quoted. The result of a $\chi^2$ confidence test comparing the observed season-dependent distribution with a uniform distribution and a McIntosh distribution are also included. With the exception of SSC onset times, all classes of events are in excess of 90% confidence level when comparing the distributions with a uniform distribution. SGC onset times fall short of the 95% confidence level by 0.5%. The peak and minimum lag each other by 12 h for SGC onset times, the time of peak activity observed in $Am$ for SSCs and SGCs (although not for the two data sets combined) and the time of peak activity measured by the $Dst$ index for all storms and SSC events. With comparison to a season-dependent McIntosh distribution, a $\chi^2$ test gives confidence levels of less than 90% for all classes of storms and it is, therefore not possible to overlook a McIntosh distribution for any of the UT variations presented.

6.4.3 Discussion

The influence of instrumental effects on the observed distributions are again considered. Asymmetries in the longitudinal distribution of reporting stations (discussed in Section 6.3.3) will not invalidate season-dependent distributions since the season-dependent activity should cancel when opposing seasons are subtracted although the distribution may be distorted. A possible bias in the season-dependent distribution could, in principle, result from latitudinal asymmetries or the reporting stations. If it is assumed that northern latitude stations are preferentially placed to detect storm onsets during northern summer, then a peak in SGC onsets would be expected in northern summer at ~0600 UT (Figure 6.7). The observed northern "summer minus winter" peak occurs in the 2100 UT to 2400 UT bin (Figure 6.8c). It is therefore unlikely that the observed season-dependent UT variation in the onset times of SGCs is a consequence of the latitudinal location of the reporting stations.

Moving now to discuss the observed distribution with respect to the models. The distribution of SSC onset times (Figure 6.8b) does not appear to be the diurnal wave of the McIntosh variation (Figure 6.2, lower panel), since the maximum and minimum of the distribution occur in adjacent bins. The $\chi^2$ test does not reject either the uniform distribution hypothesis nor the single peaked McIntosh distribution hypothesis. The SGC
onset time distribution (Figure 6.8c), however, does resemble a single peaked distribution with all but the 0600 UT to 0900 UT bin following a diurnal UT variation with the maximum and minimum of the distribution 12 h out of phase. In addition a confidence level of 94.5% is obtained using a $\chi^2$ test that the distribution is non-uniform (rising to 97.5% if SGCs 10 days either side of the equinoxes are also included). Since only 1 in 7 distributions contain the maximum and minimum separated by 12 h, there is a probability of less than 1% that the distribution of Figure 6.3c is uniform. It is therefore argued that there is a season-dependent UT variation in the onset times of SGCs. An SGC is ~4 times more likely to start between 0900 UT to 1200 UT in northern winter months than it is during northern summer months. This observed UT variation in the onset times of SGCs leads the McIntosh effect by 6 h and is the same lag observed for the double peaked seasonal independent variation discussed in Section 6.3. A possible explanation is that a magnetic disturbance commencing between 0900 UT and 1200 UT in northern winter is four times more likely to develop into a magnetic storm than a similar disturbance at the same UT in northern summer. This idea is supported by the UT distribution for SSCs (Figure 6.8b). SSCs are governed by the impact of a shock in the solar wind upon the magnetosphere and not by the orientation of the Earth’s dipole axis. Thus, if there is any UT variation present in the onset times of SSCs it is likely to be related to the growth of activity following the onset. Although the uniform distribution hypothesis for an SSC cannot be rejected, neither can the McIntosh hypothesis and the observed phase for which a minimum value of $\chi^2$ was given, leads the McIntosh effect by 6 h, in agreement with the phase difference for SGCs.

The hypothesis that the UT variation in the distribution of time of peak activity during a storm measured by the Am index (Figure 6.9) and Dst index (Figure 6.10) is uniform can confidently be rejected. Since the small samples in the 0000 UT to 0300 UT can be included in the model $\chi^2$ season-independent distributions (Figure 6.4) are included in the model $\chi^2$ season-independent distributions of the time of peak Am (Figure 6.9), the resulting confidence levels with the observed season-dependent distributions are valid. As with the UT variation in the Am index, the time of peak activity of storms measured using Am lags the McIntosh effect (i.e., the northern “winter minus summer” minimum occurs between 0600 UT and 0900 UT, whereas the McIntosh effect predicts a minimum at
0439 UT). The time of peak activity of the $D_{st}$ index during storms is between 0300 UT and 0600 UT and is thus in phase with the McIntosh effect for both categories of storm.

The season-dependent UT variation in the time of peak activity of $A_{m}$ is markedly more pronounced for SSC events (Figure 6.9b) than for SGC events (Figure 6.9c), whereas the UT variation in the time of peak activity of $D_{st}$ during SSCs and SGCs (Figures 6.10 b and c) are both markedly less convincing than peak $D_{st}$ UT distributions for both SSC and SGC events combined (Figure 6.10a). These results suggest that different mechanisms control the UT season-dependent variations in the time of peak $A_{m}$ and $D_{st}$ during storms. $D_{st}$ is an indicator of the strength of the ring current, whereas the $A_{m}$ index measures changes in the geomagnetic field and is more sensitive to auroral activity such as substorm bays.

As discussed above, the distinguishing parameter for SSCs is the solar wind dynamic pressure, whereas SGCs are dominated by the orientation of the IMF and hence reconnection processes [Section 5.4.1]. It is thus probable that the UT variation in the time of peak $A_{m}$ during magnetic storms, as well as the UT variation of the $A_{m}$ index itself, is controlled by the solar wind dynamic pressure. This conclusion is consistent with the Boller and Stolov version of the McIntosh effect. The viscous interaction, however, contributes approximately 10% of the energy coupling compared with reconnection processes [e.g. Cowley, 1984; Section 2.2.1]. It is difficult, therefore, to see how it could modulate very large disturbances to the extent shown. An alternative explanation was offered by Scurry and Russell [1990], who suggested that the Kelvin-Helmholtz instability may enhance dayside reconnection [e.g. by the patchy reconnection mechanism of La Belle-Hamer et al., 1988], which would result in the modulation of subsequent substorm activity. Since the $A_{m}$ index is sensitive to auroral substorm bays, it too will be modulated, with a delay of typically ~60 min. Such a delay is similar to the lag between the time of peak $A_{m}$ and the McIntosh effect if it is assumed that the time of peak $A_{m}$ during storms (Figure 6.9) is the same as the time of the peak in mean $A_{m}$ reported by Russell and Scurry [1990].

Kivelson and Hughes [1990] suggested that the conditions for tailside reconnection are most favourable when the tail is subject to the most stress and argued that this would occur when the geomagnetic dipole axis was at its most inclined to the Earth-Sun line.
Tail bending is absent when the dipole axis is orientated toward the dawn or dusk, allowing more energy to be stored in the tail resulting in larger substorm expansion phases and hence larger changes in the Am index. Kivelson and Hughes [1990] argued that as the axis rotates toward the Sun tail bending and hence tail stress, will increase resulting in a more rapid succession of smaller substorms and a comparatively lower value in the Am index. This mechanism would produce a UT variation roughly in phase with the McIntosh effect. Since tail bending stress will be greatest during enhanced solar wind dynamic pressure the subsequent UT variation in the Am index would be more pronounced during SSCs and is thus consistent with the observed UT variations in the time of peak Am during magnetic storms.

The measured maximum and minimum of the season-dependent variations in the time of peak activity of Dst are in different UT bins for SSCs and SGCs. The peaks in the best fit model distributions for the two types of storm, however, are in phase with each other, as well as the McIntosh effect. It is difficult to suggest a common controlling parameter for the observed variation in the time of peak Dst for both SSCs and SGCs. The SSC variation is unlikely to be a result of the Boiler and Stolov [1970] mechanism for the McIntosh effect, since that model does not offer a mechanism by which the ring current would become enhanced, whereas the Scoury and Russell and the Kivelson and Hughes mechanism would predict a UT modulation of the number of particles injected into the ring current. The UT variation in the peak activity of Dst during SGCs is, on the other hand, likely to be controlled by a reconnection mechanism. Crooker and Siscoe [1986] predicted a UT variation in the efficiency of energy coupling of reconnection. When $\psi$, the angle between the Earth’s magnetic dipole axis and the Earth-Sun line, is at a minimum open tail flux will partly obscure the polar cusp, inhibiting reconnection. The UT variation in coupling efficiency will therefore be in phase with the McIntosh effect. The UT variation in energy coupling in the model of Crooker and Siscoe is dependent upon IMF $B_z$ rather than the solar wind pressure and would therefore result in a more pronounced UT variation in the reconnection dominated SGCs than the solar wind driven SSCs.
6.5 Summary

In this chapter seasonal and universal time variations of both SSCs and SGCs have been investigated. The semi-annual variation in the occurrence of storms is found to apply only to SGCs, although “great” SSCs do exhibit a semi-annual variation. This suggests that the solar cause of an SSC is different to that of an SGC. Since the distinguishing parameter of SSCs is solar wind dynamic pressure [Chapter 5] it is concluded that the heliospheric latitude model of geomagnetic activity is ineffective in modulating the previously observed semi-annual variation in the occurrence of magnetic storms.

The analysis also indicates that there are both season-dependent and season-independent UT variations in the onset times of SGCs and the time of peak Dst and Am indices during storms. There is evidence of several different mechanisms at work and in this chapter an attempt has been made to separate them. The season-independent variation in the onset times of SGCs contains two components, one is semi-diurnal and is 6 h out of phase with the McIntosh effect. The other component is diurnal, peaking between 0300 UT and 0600 UT and is possibly a response to longitudinal asymmetries in the Earth’s magnetic field. The season-dependent UT variation in the onset times of SGCs is diurnal and leads the McIntosh effect by ~6 h, thus both season-dependent and the semi-diurnal season-independent variations in the onset times of SGCs lead the McIntosh effect by 6 h. A possible explanation for the phase of the UT variation in the onset times of SGCs is that at certain times during the day, a disturbance of a given magnitude is more likely to develop into a magnetic storm due to later UT variations in magnetospheric coupling between the solar wind and IMF.

Season-dependent variations in the time of peak activity of Am during storms are in phase with the observed UT variation of the Am index and are more pronounced for SSCs than for SGCs, suggesting that the UT activity of the Am index is driven by the solar wind, possibly a result of the Scurry and Russell version of the McIntosh effect based on patchy reconnection [La Belle-Hamer et al., 1988] and/or by magnetotail stress model of Kivelson and Hughes [1990]. The season-dependent UT variation of peak activity of Dst is similar for both SSCs and SGCs. It is suggested that the time of peak Dst activity observed in SSCs is the result of the Scurry and Russell [1990] version of the McIntosh effect and that the time of the Dst peak during SGCs is governed by the energy...
coupling efficiency model of Crooker and Siscoe [1986]. A season-independent component in the time of peak Dst activity has also been observed and found to mimic the UT variation of the Dst index reported by Saroso et al. [1992]. However, since the observed season-independent UT variation in the peak Dst is found to be more pronounced for SGCs than for SSCs and in phase with the UT variations in the Dst index reported by Mayaud [1980], it is suggested that the observed UT variation may be due to limitations in the Dst index.
CHAPTER 7

Conclusions

7.1 Introduction

This thesis describes a study into the cause of magnetic disturbances in the Earth's ionosphere. Although the results obtained are somewhat limited for the purpose of magnetic forecasting, they increase our understanding of when and how magnetic storms occur. Clarification has been obtained on the effectiveness of existing coupling models and the magnetospheric response to different solar wind input conditions has been characterised. The study has utilised both statistical analysis and an individual case study. The data sources include 5 ionospheric radars, 3 digisondes, 17 solar wind and IMF monitoring spacecraft and 44 individual magnetometer stations. In addition 4 geomagnetic indices have been employed comprising of data from 47 contributing stations, resulting in a total of 104 separate instruments contributing to this study.

7.2 Summary of Principal Results

In this study, a magnetic storm has been defined as an event for which $D_{st}$ falls below $-50$ nT for four consecutive hours. Storms have been divided into SSCs (storm sudden commencements; all storms initiated by a sudden commencement) and SGCs (storm gradual commencements; all other storms) and studied as separate entities. The results of a superposed epoch analysis demonstrate that SSCs and SGCs are, in general, caused by different solar phenomena. SSCs are the result of the impact of a CME upon the magnetosphere and driven primarily by enhanced solar wind pressure, whereas an SGC is the result of the interaction of the geomagnetic field with enhanced $B_z$ associated with the Earth passage of a high-speed/low-speed stream interface in the solar wind. The largest magnetic storms are SSCs, moreover it is a large solar wind velocity (i.e. a fast moving CME) which is the important parameter in generating the largest geomagnetic disturbances. Since large SSCs are also associated with exceptionally large values of $B_z$ it is suggested that the high speed CMEs cause the more extreme compressions in the IMF.
and that the resultant magnetic disturbance is driven by both large IMF $B_z$ and rapid changes in the solar wind dynamic pressure. The dominant sign of $B_z$ in the 12 h to 24 h preceding a magnetic storm onset is found to be the sign of $B_z$ directly after. If $B_z$ is positive directly after the onset, the resultant magnetic activity is slow to develop and is dependent upon a rapid injection of energy once $B_z$ has turned negative.

The different causes of SSCs and SGCs is also highlighted in a seasonal study of magnetic storm occurrence statistics. It is demonstrated that the semi-annual variation of magnetic storms, with peak occurrence near the equinoxes, occurs only for SGC events. This is consistent with the earlier conclusion concerning the solar origin of SSCs and SGCs. Since the controlling parameter of SGCs is enhanced IMF $B_z$ resulting from a high-speed/low-speed stream interface in the solar wind, the enhanced $B_z$ will be modulated by the Russell and McPherron effect and thus the resultant SGC occurrences will also be modulated. SSCs, on the other hand, are primarily the result of the enhanced pressure and shock impact on the magnetosphere from the Earth passage of a CME. Since there is no seasonal modulation of SSCs and since SSCs are associated with enhanced solar wind pressure, it is implied that the solar wind pressure does not play a leading role in the modulation of the semi-annual variation in the occurrence of magnetic storms. This rules out both the heliospheric latitude effect and the Boller and Stolov version of the McIntosh effect as the principal mechanism for generating the observed variations.

UT variations are also apparent in the occurrence statistics of storms in both the onset times of SGCs and in the peak in the $Am$ and $Dst$ magnetic indices during both SSCs and SGCs. Both the season dependent and the semi-diurnal season independent variations lead the modulation predicted by the McIntosh effect by 6 h. It is suggested that a magnetic disturbance of a given magnitude at a certain UT may be more likely to develop into a magnetic storm than a similar disturbance at a different UT due to subsequent UT modulation in the energy coupling between the geomagnetic field and the solar wind and IMF.

The season dependent UT variation in the time of peak $Am$ during a magnetic storms lags the modulation predicted by the McIntosh effect by 3 h and is more pronounced for SSCs than for SGCs (the observed season dependent variation in the $Am$ itself in fact lagged the McIntosh effect by ~3 h). It is also concluded that since the
SSCs are solar wind pressure dominated the principle mechanism for the coupling of the solar wind/IMF to the magnetosphere of the McIntosh effect must be solar wind controlled and it is suggested that the Kivelson and Hughes magnetotail stress model and the Scurry and Russell suggestion that the Kelvin-Helmholtz instability may enhance the reconnection process may be the principal coupling mechanisms in modulating the UT variation present in the Am during storms and also in the Am index.

The season dependent peak in Dst during a magnetic storm is found to be in phase with the McIntosh effect for all classes of storm and it is not safe to distinguish between the UT variation during SSCs and SGCs. It is concluded that the Crooker and Siscoe model on the limits of dayside reconnection may be responsible, in part, for the observed UT variation of peak Dst during SGCs and that the Kivelson and Hughes and the Scurry and Russell models may play a more dominant role in modulating Dst during SSCs.

A detailed case study of a magnetic storm which occurred on 20–21 March 1990 has also been undertaken. The study utilised data from three northern hemisphere incoherent scatter radars; two coherent scatter radars and three digisondes, giving a total of 8 instruments providing measurements of bulk ionospheric flow. In addition the study employed data from 44 magnetometer stations as well as solar wind plasma and IMF data from the IMP-8 spacecraft. The storm has been studied as two intervals; the first of which included the SSC which was in response to a shock front in the solar wind pressure striking the magnetopause simultaneously with a southward turning of the IMF; the second interval included the resumption of magnetic activity in response to a southward turning of the IMF only. The initial response time of the ionosphere on the nightside to the southward turning at the magnetopause during the shocked solar wind impact was ~10 min, considerably less than the response time of the nightside ionosphere to a southward turning measured by Lester et al. [1993] and more in agreement with the dayside response times to changes in polarity of $B_z$ measured by Etemadi et al. [1988] and Todd et al. [1988]. The response times of the magnetosphere and the ionosphere to the southward turning during interval 2 range from ~15 min on the dayside to ~60 min near midnight consistent with the studies of Etemadi et al. [1988], Todd et al. [1988] and Lester et al. [1993]. A latitudinal dependence in the response time of the ionosphere is also demonstrated, with the response time to changes in the polarity of $B_z$ at the
magnetopause increasing by between 1 min to 2 min per degree of equatorward latitude.

The analysis indicates that open flux entering the magnetosphere during the initial few hours following the onset of the SSC is consistent with Faraday's Law within the uncertainty of the crude approximation, although a better fit is obtained if an elliptically expanding polar cap is assumed. It is also demonstrated that the nightside convection pattern can be strongly influenced by a substorm expansion phase. Two instances of reconfiguration of the nightside pattern have been studied, both of which were coincident with substorm expansion phase onsets. The first instance, although occurring during an interval for which there was no IMF data available, is reminiscent of a change in convection under negative $B_y$ to a configuration more associated with a positive $B_y$. The IMF $Y$ component was predominantly negative before the data gap, which began 20 min prior to the reconfiguration and AMIE models suggest that the IMF was positive after the reconfiguration. In this instance it is not possible to separate substorm effects from $B_y$ effects and it is suggested that both may have played a role during the reconfiguration. The second reconfiguration, which also occurred simultaneously with a substorm expansion phase onset, was not associated with any change in the IMF. In this instance the nightside flow reversal appeared to move eastward with the substorm current system located near the nightside flow reversal boundary. In summary, with the exception of response times of the magnetosphere to changes in the IMF and solar wind energy input, the case study demonstrates that the magnetospheric and ionospheric convection during this particular magnetic storm is generally consistent with observations and models of magnetospheric and ionospheric convection during less extreme conditions in the solar wind and IMF energy input. The response times to the southward turning accompanied by a shocked impact were considerably less than previous observations under normal input conditions.

**7.3 Suggestions for Future Work**

Although this thesis employs large data sets, the primary limitation of the research presented is the extent of the available data. The analysis of Chapters 5 and 6 are based on a sample of 538 storms, 230 SGCs and 308 SSCs. Although for much of the studies undertaken this was a sufficient number, there were too few large ($Dst \leq -100$ nT) for four
consecutive hours) SGCs for a superposed epoch analysis, particularly as solar wind and IMF data are available for ~50% of the time. There are sufficient events to strongly suggest that there is a UT variation in the onset times of SGCs, although the number of events is insufficient to prove its existence, or to investigate to what extent the intensity of the storm has upon the variation. A larger data set would clarify these points and may help in the determination of the causes.

Storms have been defined by the \( Dst \) magnetic index. As stated in Section 5.2, \( Dst \) may not always be a good indicator of storm activity. The results of the superposed epoch analysis in Chapter 5 and the UT variations in the time of peak activity of \( Dst \) and \( A_m \) presented in Chapter 6 demonstrate different indices behave in different ways during storms. Defining storms by another index, such as \( Kp \) or \( AE \), may increase the size of the data set and highlight different mechanism for their generation.

A case study of the local time and latitudinal dependence of the response times to changes in the IMF at the magnetopause has been undertaken in this thesis (Chapter 4). Further investigation of ionospheric convection response to changes in \( B_z \) under different solar wind plasma conditions are necessary to determine which factors are responsible for the more rapid response to the southward turning associated with the SSC. In this thesis and in earlier studies consideration has been given to the time taken for a response to be detected rather than measuring the time at which particularly disturbed activity commenced. In 1992, Intermagnet became operational making minute resolution ground magnetometer data from over 40 (and increasing) participating stations freely available. The large data base available form Intermagnet will enable the investigation of response times to be extended, by both case and statistical studies, to include the subsequent local time and latitudinal development of the storm.

The March 1990 magnetic storm case study is very much a precursor to the type of study which will be possible when the new SuperDARN network of coherent radars are operational in the near future [Greenwald, 1992]. The study in this thesis generated patchy "snap shots" of the global ionospheric convection pattern by plotting short time series of ionospheric flow from different instruments at the appropriate local time. Thus, although some gross characteristics of the convection pattern could be inferred, there are spatial and temporal uncertainties. The SuperDARN network will consist of up to 4
bistatic HF coherent radars in the northern hemisphere covering approximately half of the northern auroral ionosphere and three radars in the southern hemisphere and will have a temporal resolution between 6 s and 96 s (dependent on the spatial extent of the scan). Although it is unlikely that the all radars will simultaneously record backscatter, the observed backscatter will, in general, occupy a considerably larger area than is at present available and will allow a much more detailed study of the ionospheric (and hence the magnetospheric) convection pattern in response to changes in the solar wind and IMF energy input.

In addition to the improvement of data coverage on the ground, the mid-nineties sees launch of the SOHO and CLUSTER spacecraft [Domíngo et al., 1988]. SOHO will occupy a halo orbit at the $L_1$ Lagrangian neutral point and will undertake a variety of measurements of both solar and solar wind phenomena. This will allow continual monitoring of the solar wind. Sadly, however, there is to be no magnetometer installed on SOHO. CLUSTER comprises four spacecraft and its principal aim is to monitor, in three dimensions, the solar wind and IMF with no ambiguity resulting from temporal changes. Data from these spacecraft will help clarify the nature of the solar wind phenomena which cause magnetic storms.
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