

**EXPERIMENTAL AND THEORETICAL
ANALYSES OF SOLAR WIND -
MAGNETOSPHERE - IONOSPHERE COUPLING.**

Mervyn Paul Freeman.

Thesis submitted for the degree of Doctor of Philosophy of the University of London,
and for the Diploma of Membership of Imperial College.

October 1989.

Department of Physics,

Imperial College of Science, Technology, and Medicine,

London SW7 2BZ.

To My Parents.

From Man or Angel the great Architect
Did wisely to conceal, and not divulge
His secrets, to be scanned by them who ought
Rather admire. Or, if they list to try
Conjecture, he his fabric of the Heavens
Hath left to their disputes - perhaps to move
His laughter at their quaint opinions wide
Hereafter, when they come to model Heaven
And calculate the stars: how will they wield
The mighty frame: how build, unbuild, contrive
To save appearances; how gird the Sphere
With Centric and Eccentric scribbled o'er,
Cycle and Epicycle, Orb in Orb.

(John Milton, *Paradise Lost*, 1667).

Contents.

	Page
Abstract.	13
Acknowledgements.	14
Chapter 1. Introduction.	15
1.1. Early Auroral Observations.	16
1.2. The Solar Wind and Magnetosphere.	16
1.3. Magnetospheric Convection.	22
1.4. Magnetosphere-Ionosphere Coupling.	25
1.5. The Magnetospheric Substorm.	28
Chapter 2. A Model of Quasi-Steady Ionospheric Convection and Evidence for Time-Dependent Phenomena.	32
2.1. Preface.	33
2.2. Introduction.	33
2.2.1. Preliminary discussion.	33
2.3. The Ionospheric Flow Model.	40
2.4. Results.	43
2.4.1. Steady state convection.	43
2.4.1. (i) Reconnection across the whole dayside magnetopause.	43
2.4.1. (ii) Localised reconnection about noon MLT.	45
2.4.2. Non-steady state convection.	45
2.4.2. (iii) Magnetospheric erosion. Irregular polar cap boundary. Flux return event. Collapse of boundary bulge.	47 49
2.4.2. (iv) Magnetospheric erosion. Uniform polar cap boundary.	51
2.5. Discussion of Model Results.	53
2.6. Observations.	54
2.7. Conclusions.	62
Chapter 3. Pressure-driven Magnetopause Motions and Attendant Response on the Ground.	64
3.1. Preface.	65
3.2. Introduction.	65
3.3. Data Overview.	69
3.3.1. Solar wind and magnetopause observations.	69

	Page
3.3.2. <i>Ground magnetometer recordings.</i>	76
3.4. Analysis.	81
3.4.1. <i>Signal timing and magnetopause motion.</i>	81
3.4.2. <i>Ground response to solar wind ram pressure changes and magnetopause motion.</i>	86
3.4.3. <i>Ground signatures of FTEs?</i>	88
3.4.4. <i>Global characteristics of the ground disturbance.</i>	90
3.5. Conclusions.	92
 Chapter 4. The Control of Dayside Ionospheric Convection and Magnetospheric Topology by Magnetic Reconnection between the IMF and the geomagnetic field. A Case Study - September 4, 1984.	 95
4.1. Introduction.	96
4.2. Data Overview and Analysis.	98
4.2.1. <i>State of the magnetosphere.</i>	98
4.2.2. <i>Spacecraft data.</i>	99
4.2.2. (i) <i>IMF observations.</i>	100
4.2.2. (ii) <i>Magnetopause observations.</i>	101
4.2.2. (iii) <i>Low altitude particle data.</i>	104
4.2.3. <i>Ground data.</i>	108
4.2.3. (i) <i>Riometer and ionosonde data.</i>	108
4.2.3. (ii) <i>Syowa radar data.</i>	115
4.2.3. (iii) <i>Scandinavian magnetometer data.</i>	119
4.2.3. (iv) <i>SABRE radar data.</i>	130
4.3. Discussion.	133
4.4. Conclusion.	142
 Chapter 5. Measurements of Field-Aligned Currents by the SABRE Coherent Scatter Radar.	 143
5.1. Introduction.	144
5.2. The SABRE Radar.	144
5.3. Analysis Technique.	151
5.3.1. <i>The divergence field.</i>	151
5.3.2. <i>The vorticity field.</i>	152
5.4. Method for the Evaluation of the Divergence and Vorticity Fields.	153

	Page
5.5. Sources of Error.	154
5.6. Results.	159
5.7. Discussion and Conclusion.	166
 Chapter 6. Conclusion.	 170
6.1. Introduction.	171
6.2. The Effect of Solar Wind Pressure on the Magnetosphere-Ionosphere System.	 171
6.3. The Response of the Magnetosphere-Ionosphere System to Inferred Changes in the Reconnection Rate.	 172
6.4. The Magnetosphere-Ionosphere Coupling Agent: Field-Aligned Current.	 175
 References.	 177

List of Figures.

	Page
1.1 Interplanetary magnetic field lines in the solar ecliptic plane.	18
1.2. Three-dimensional sketch of the heliospheric current sheet.	19
1.3. Gas-dynamic model of the magnetosheath velocity field.	21
1.4. Flow streamlines in the magnetospheric equatorial plane due to momentum transfer from the solar wind by a viscous interaction at the magnetospheric boundary.	22
1.5. Dungey's model of the magnetosphere for southward and northward IMF.	23
1.6. An idealised model of the field-aligned currents required to couple magnetospheric flow to the ionosphere.	26
1.7. The electric field or Pedersen current pattern associated with the two-cell ionospheric convection pattern.	27
1.8. The distribution and polarity of large-scale field-aligned currents at high geomagnetic latitudes.	28
1.9. Time sequence of changes in the magnetic field and plasma in the Earth's magnetic tail during a substorm.	29
2.1. Sketches of the modified two cell ionospheric convection pattern due to:	
a. dayside reconnection alone,	
b. nightside reconnection alone,	
c. concurrent, but unbalanced, dayside and nightside reconnection with the dayside reconnection dominant.	36
2.2. Expected temporal evolution of the ionospheric footprint of newly reconnected magnetic flux, arising from an imbalance between dayside and nightside reconnection rates.	
a. A dayside polar cap boundary bulge.	
b. A nightside polar cap boundary bulge.	39
2.3.a. Expected dayside ionospheric flow streamlines due to steady-state reconnection across the whole dayside magnetopause.	
b. Resultant latitudinal flow profiles at selected magnetic local times.	44
2.4.a. Expected dayside ionospheric flow streamlines due to steady-state localised reconnection at the dayside magnetopause.	
b. Resultant latitudinal flow profiles at selected magnetic local times.	46

	Page
2.5.a. Expected dayside ionospheric flow streamlines due to localised erosion at the dayside magnetopause.	
b. Resultant latitudinal flow profiles at selected magnetic local times.	48
2.6.a. Expected dayside ionospheric flow streamlines due to a "flux return event".	
b. Resultant latitudinal flow profiles at selected magnetic local times.	50
2.7.a. Expected ionospheric flow streamlines due to a uniform polar cap expansion arising from magnetospheric erosion.	
b. Resultant latitudinal flow profiles at selected magnetic local times.	52
2.8. The viewing areas of the SABRE radars.	54
2.9. A comparison of measured ionospheric flow velocity components with those derived from the uniform polar cap expansion model.	
a. Using SABRE radar data.	
b. Using Scandinavian magnetometer data.	56
2.10. The diurnal convection pattern measured by SABRE, averaged over all magnetic conditions.	59
2.11. Comparison of the diurnal convection pattern measured by SABRE with that expected due to a model ionospheric convection pattern.	60
3.1. IMP 8 solar wind plasma and magnetic field data; 22:00 - 03:00 UT, September 9-10, 1978.	69
3.2. ISEE 1/2 magnetic field data from the magnetopause vicinity.	
a. 23:30 - 00:30 UT, September 9-10, 1978.	72
b. 00:30 - 01:30 UT, September 10, 1978.	74
c. 01:30 - 02:30 UT, September 10, 1978.	75
3.3. A schematic showing the relative positions of the spacecraft in the ecliptic plane and typical bow shock and magnetopause.	70
3.4. Ground magnetometer data from eight high latitude stations; 00:00 - 02:30 UT, September 10, 1978.	
a. X component of the geomagnetic field.	78
b. Y component of the geomagnetic field.	79
c. Z component of the geomagnetic field.	80
3.5. ISEE 1/2 trajectories superposed on a modelled magnetopause location.	83
3.6. Radial speeds of the magnetopause boundary versus Universal Time at IMP 8.	85

	Page
3.7. A comparison of the time-varying solar wind dynamic pressure at the IMP 8 spacecraft with the X component of the geomagnetic field at station AVI and magnetopause speeds measured by ISEE 1 and 2.	87
3.8. A comparison of measured geomagnetic field components at two ground stations with FTE models.	89
3.9. X component of the geomagnetic field for eight ground stations; 00:45 - 02:15 UT, September 10, 1978.	91
4.1. An illustration of the major changes in magnetospheric topology during the substorm growth phase.	96
4.2. ISEE 2 and AMPTE-UKS and -IRM spacecraft trajectories; 12:00 - 16:00 UT, September 4, 1984.	
a. In the X-Y (GSM) plane.	
b. In the X-Z (GSM) plane.	99
4.3. ISEE 2 magnetic field data; 12:00 - 15:10 UT, September 4, 1984.	100
4.4.a. AMPTE-UKS magnetic field data; 13:00 - 14:50 UT, September 4, 1984.	101
b. AMPTE-IRM magnetic field and plasma data; 13:10 - 15:10 UT, September 4, 1984.	103
4.5. DMSP-F7 precipitating particle data on September 4, 1984.	
a. 12:12 - 12:32 UT.	105
b. 14:46 - 15:06 UT.	
c. 15:35 - 15:55 UT.	106
4.6. Syowa riometer data; 09:00 - 21:00 UT, September 4, 1984.	109
4.7. Halley Bay ionosonde data on September 4, 1984.	
a. 14:00 UT.	
b. 15:00 UT.	110
4.8. Syowa ionosonde data on September 4, 1984.	
a. 13:30 UT.	112
b. 13:45 UT.	
c. 15:00 UT.	113
4.9. Syowa radar data on September 4, 1984.	
a. 12:00 - 14:00 UT.	
b. 14:00 - 16:00 UT.	116
c. 16:00 - 18:00 UT.	117

	Page
4.10. Ground magnetometer data; 12:00 - 18:00 UT, September 4, 1984.	
a. From Syowa.	
b. From Kilpisjarvi.	121
4.11. Latitudinal profiles at 13:40, 14:00, and 14:30 UT on September 4, 1984 of:	
a. the northward geomagnetic field perturbation,	
b. the westward E-region electron drift speed.	124
4.12. The geometry of a simplified ionospheric Hall current distribution and its ground magnetic effect.	125
4.13.a. The latitudinal profile of an idealised ionospheric Hall current system.	
b. The resultant north-south ground magnetic perturbation.	
c. The resultant east-west ground magnetic perturbation.	128
4.14. Ionospheric flow components recorded near to the centre of the SABRE field of view; 12:00 - 18:00 UT, September 4, 1984.	130
4.15. Estimated location of the polar cap boundary versus Universal Time on September 4, 1984.	134
4.16. Ground magnetometer data from College, Alaska; 12:00 - 18:00 UT, September 4, 1984.	141
5.1. The location and field of view of the SABRE radars.	145
5.2. A "snapshot" of the ionospheric electron drift velocity field over the SABRE field of view.	150
5.3. Calculations using discretised measurements of the velocity field of an azimuthally gyrating fluid.	
a. Divergence field.	
b. Vorticity field.	157
5.4. Calculations using discretised measurements of the velocity field of a discontinuous flow shear.	
a, c. Divergence field.	
b, d. Vorticity field.	158
5.5. The ionospheric electron drift velocity measured over three areas in the SABRE field of view; 14:00 - 15:50 UT, September 4, 1984.	160
5.6.a. The divergence field, and	
b. the vorticity field	
over the SABRE field of view at 14:15 UT, September 4, 1984.	162

	Page
5.7.a. The divergence field, and	
b. the vorticity field	
over the SABRE field of view at 14:35 UT, September 4, 1984.	164
5.8.a. The divergence field, and	
b. the vorticity field	
over the SABRE field of view at 14:50 UT, September 4, 1984.	165
5.9. The Birkeland current systems in the middle magnetosphere arising from magnetospheric erosion.	168

List of Tables.

	Page
1.1. Physical Properties of the Solar Wind at Earth Orbit.	19
3.1. Ground Magnetometer Stations.	77
4.1. Ground Observing Stations.	108

Abstract.

The coupling of the solar wind to the terrestrial magnetosphere and ionosphere is investigated by both a theoretical approach and experimental methods which embrace spacecraft, radar and other ground data. Particular emphasis is placed upon the time-dependent nature of the coupling. The transient behaviour of the magnetosphere-ionosphere system yields important information on the coupling mechanisms. The essential features of the solar-terrestrial system are introduced and the evidence for alternative coupling mechanisms to drive the steady-state magnetospheric convection are reviewed. The coupling by field-aligned currents of the magnetosphere to its lower boundary, the ionosphere, is considered. A model to quantitatively describe the quasi-steady large-scale ionospheric convection pattern in the auroral region is developed. The effect of different coupling phenomena on the convection is considered by employing appropriate high-latitude boundary conditions. Comparison with data is fair, but underlines the essentially time-dependent nature of the system. By a case study we demonstrate how changes in the solar wind plasma pressure can affect the magnetospheric system and couple to the ionosphere to drive transient motions therein. We find the ground response to depend critically on the character of the source and the observing position. The study highlights the need for the careful definition and identification of the observational signatures of different coupling mechanisms. On longer time scales, we study the evolution of a magnetospheric substorm. Concurrent observations in space and on the ground are used to show the control of ionospheric convection and magnetospheric topology by reconnection between the interplanetary and terrestrial magnetic fields. Spacecraft observations show the dayside magnetosphere to erode as magnetic flux is transported to the nightside. The topological change of the magnetosphere is confirmed by concurrent ground observations. Subsequently, the nett flux transfer is reversed by a substorm onset in the geomagnetic tail. During the same substorm sequence we analyse in detail the ionospheric flow data from the SABRE coherent scatter radar. A new technique is developed to measure magnetospheric field-aligned currents from the flow data. The technique is used to identify and analyse a localised upward field-aligned current sheet in the late afternoon mid-latitude ionosphere which is interpreted as being generated by the ring current in response to the prevailing magnetospheric erosion.

Acknowledgements.

I am grateful to my supervisor, *Prof. D. J. Southwood*, for his encouragement and direction throughout the course of my studentship. I would also like to thank my colleagues and friends at Imperial College and elsewhere for freely giving me their time, energy and resources. Particular thanks go to *C. J. Farrugia*, *M. Lester*, *M. Lockwood*, *A. S. Rodger*, and *J. A. Waldock* for the interest they have taken in this research.

I acknowledge with thanks the support provided by the Science and Engineering Research Council by the provision of a studentship.

Data for this thesis has been kindly provided by the following: *J. A. Waldock**, *M. Lester* (Leicester University, *now at Sheffield City Polytechnic), SABRE radar; *A. S. Rodger* (British Antarctic Survey, Cambridge), Halley Bay ionosonde; *T. Ogawa* (National Institute for Polar Research, Tokyo), Syowa riometer, ionosonde, magnetometer, and radar; *P. Newell*, (Applied Physics Lab., Maryland), DMSP electron and ion instruments; *J. Sommer*, (Danish Meteorological Institute, Copenhagen), Scandinavian magnetometers; *W. Baumjohann*, (Max-Planck Institut für Physik und Astrophysik, Garching), AMPTE-IRM magnetometer and plasma instrument; *M. W. Dunlop*, (Imperial College, London), AMPTE-UKS magnetometer; *C. T. Russell*, (University of California, Los Angeles), ISEE 1/2 magnetometer; *N. Sckopke*, (Max-Planck Institut für Physik und Astrophysik, Garching), ISEE 1/2 plasma instrument; *R. Lepping*, (Goddard Space Flight Center, Maryland), IMP 8 plasma instrument and magnetometer.

Finally, I thank *Sarah Smith* for her patience and love during the course of this study, and for preserving my sanity!

CHAPTER 1

INTRODUCTION.

1.1. Early Auroral Observations.

Documentary evidence of auroral sightings is to be found in Chinese (Chu-Shu-Chi-Nien, ~ 2600 B.C.), biblical (Ezekiel 1: 1-28, 593 B.C.), Greek (Plutarch, 467 B.C.), and Roman (Livy; Dionysius, ~ 460 B.C.) literature. The Roman historian, Seneca, reported that in 37 A. D. Tiberius Caesar sent his army to the southern Italian port of Ostia, believed to be under enemy attack, because the red auroral light was mistaken for his fleet being on fire (see Eather, 1980; for these and other references). Only in the last 50 years has Man begun to seriously contemplate and understand the subtle interaction between the tenuous extremum of the solar atmosphere and the Earth's magnetic field, the physics of which generated the phenomenon observed nearly 2000 years earlier.

In the early 18th Century scientific studies of the aurora were initiated by regular sightings of it over the more heavily populated and culturally advanced areas of Europe (e.g. southern England, France, Germany), from where it had previously been absent. The return of the aurora to these lower latitudes coincided with the end of a prolonged period of minimal solar activity, known as the Maunder minimum (Eddy, 1976). By examination of earlier records from geographically disparate sources two key facts about the aurora were established by the early geophysicists, indicative of its geomagnetic and solar origin (Siscoe, 1980; and references therein): (a) The auroral occurrence frequency at a given location was correlated with solar activity, measured by sunspot number. Thus auroral occurrence was modulated by the 11 year solar cycle. (b) auroral variations in the United States and Europe were similar and positions of constant auroral occurrence frequency (isochasms) were latitude dependent. Phenomena associated with the aurora and the cause of its latitudinal migration are considered in Chapters 2 and 4.

1.2. The Solar Wind and Magnetosphere.

The next significant advance in solar-terrestrial physics arose from studies of the geomagnetic field, recorded primarily for navigational purposes. Rapid increases in the equatorial field at the Earth's surface were detected which were clearly too impulsive to be due to geological effects internal to the Earth. Chapman and Ferraro (1930) postulated that a current sheet was formed in space, located several Earth radii (R_E) from the Earth's surface, due to the interaction of plasma with the Earth's magnetic field.

In their model they assumed a neutral stream of ionised matter emanating from the Sun and flowing past the Earth. The effect of the geomagnetic field would be to form a cavity in this plasma stream. The boundary between the geomagnetic field cavity and the plasma stream would be a current sheet whose sense and strength would be such as to switch off the geomagnetic field outside the cavity and compress the field within, so that its magnetic

pressure would stand off the dynamic and thermal pressure of the plasma stream. The cavity is known as the magnetosphere and its outer boundary is called the magnetopause.

If the dynamic pressure of the plasma stream increased rapidly, due to an enhancement in density or speed, the current sheet equilibrium would be altered, the cavity boundary would move earthwards and the current sheet intensify. This phenomenon could then explain the rapid enhancements in the equatorial geomagnetic field which were to become known as Sudden Impulses (SI). We shall consider the detailed temporal response of the magnetospheric system to changes in the plasma stream pressure in Chapter 3.

Further evidence for the existence of a plasma stream of solar origin was cited by Biermann (1951) in his examination of cometary tails. It was observed that a comet has two distinct tails, Type I and Type II. The latter tail is curved, structureless, and comprised mainly of dust particles. Particle accelerations observed in the Type II tail are of the same order as the acceleration due to solar gravity at the comet location and can be explained by solar radiation pressure. The Type I tail is straight, structured, and composed of ionised matter. Particle accelerations greatly exceed those measured in the dust tail and led Biermann to propose an interaction between sublimated, ionised cometary material and a solar plasma stream. A measurement of the velocity of the stream could be made by observing the direction of the Type I comet tail. The tail was found to be not quite in the radial direction, but lagged slightly behind the cometary motion. The orbital speed of a comet is typically $30\text{-}50 \text{ kms}^{-1}$ perpendicular to the solar radius vector and so the observed angular aberrations of $3^\circ\text{-}6^\circ$ predicted a plasma streaming very close to the radial direction away from the Sun at a few hundred kms^{-1} .

Parker (1958; 1960) then demonstrated that the solar corona should be continually expanding and that the plasma flow should turn supersonic at some radial distance. He christened the plasma outflow the "solar wind". Simple, steady state, spherically symmetric models allowed the spatial distribution of the plasma properties to be calculated for given measured solar coronal conditions.

Parker (1958) also considered the effect the solar wind might have on a solar magnetic field. Alfvén had earlier developed a theory of magnetic field evolution in a highly conducting, moving plasma. In the limit of infinite conductivity, the steady state magnetic field could be shown to convect with the flow such that a fluid element would always be attached to the same field line (e.g. Alfvén, 1950). This important concept, known as the "frozen-in" field theorem is best expressed by saying that the electric field in the frame of the moving fluid element is zero. i.e.

$$\mathbf{E} + \mathbf{V} \times \mathbf{B} = 0 \quad (1.1)$$

In most regions of space, except at thin boundaries between different plasma or field regimes, the "frozen-in" field theorem is thought to be a very good approximation (e.g. Freeman and Southwood, 1988b; and references therein).

By assuming the field to be carried along with the solar wind Parker was able to predict the strength and direction of the Interplanetary Magnetic Field (IMF). Due to the solar rotation the IMF adopted an Archimedean spiral or "garden hose" orientation such that the angle between the radial vector, approximately the solar wind velocity vector, and the IMF was about 45° at Earth orbit. The field configuration in the ecliptic plane is shown in Fig. 1.1.

The early spacecraft missions in the 1960's directly measured the solar wind and showed the plasma outflow to be continuous and radially directed to within $\sim 10^\circ$, as contended by Parker. The physical properties of the solar wind are summarised in Table 1.1 (Fälthamar, 1973, and references therein).

Magnetic field measurements showed there to be also a weak interplanetary magnetic field of a few nano-Tesla (nT). Its time-averaged orientation was a striking success for the Parker model: it showed the IMF to be generally pointing either away or toward the Sun at an azimuthal deflection close to 45° from the Sun-Earth line.

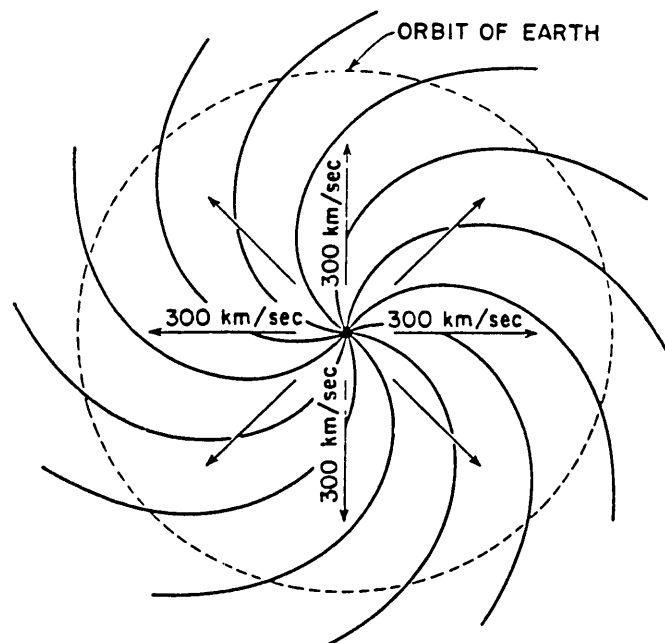


Fig. 1.1. Interplanetary magnetic field lines in the solar ecliptic plane due to the extension of the solar magnetic field by a uniform 300 km s^{-1} quiet time solar wind (from Parker, 1964).

Table 1.1 - Physical Properties of the Solar Wind at Earth Orbit.

Conditions	Quiet	All
Number density (cm^{-3})	9	2 - 20
Speed (km s^{-1})	320	250 - 700
Proton Temperature ($^{\circ}\text{K}$)	4×10^4	$1 \times 10^4 - 2 \times 10^5$
Electron Temperature ($^{\circ}\text{K}$)	1.5×10^5	$\sim 1 - 2 \times 10^5$
IMF magnitude (nT)	5	1 - 15

The polarity of the magnetic field line blown outwards from the solar surface determines whether the IMF detected at Earth orbit points away or toward the Sun. For prolonged intervals ($\sim$ months) the IMF could be ordered in solar longitude into several "away" and "toward" sectors. This observation and the generally strong ecliptic component of the IMF showed the solar magnetic field to be non-dipolar. The results were interpreted as showing the presence of a heliospheric current sheet dividing in the solar magnetic equatorial plane the oppositely directed field lines blown out from the magnetically opposed northern and southern solar hemispheres. By assuming the solar magnetic equatorial plane to be inclined to the ecliptic plane a two-sector structure to the IMF at Earth orbit could be readily explained. More sectors implied the current sheet to be wavy, rotating in space like the skirt hem of a pirouetting dancer (Smith et al., 1978). This "ballerina" model is shown in Fig. 1.2.

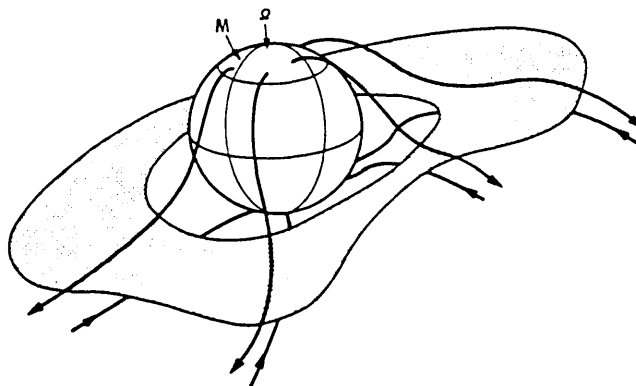


Fig. 1.2. Three-dimensional sketch of the heliospheric current sheet (shaded area), separating the spiralled IMF lines emanating from regions of opposite magnetic polarity in the northern and southern solar hemispheres. The current sheet is shown lying near to the solar equatorial plane, but inclined to it due to the tilt of the solar magnetic dipole with respect to the solar rotation axis. The current sheet is also rippled to account for the observation of multi-sector IMF structure by satellites in the ecliptic plane (from Smith et al., 1978).

The ripples in the heliospheric current sheet and the tilt of the solar magnetic equatorial plane mean that the IMF has a variable component out of the ecliptic plane and parallel to the geomagnetic field. This north-south field component has been found to strongly modulate the coupling of the IMF to the terrestrial field, as we shall discuss later in this chapter, and consider in Chapter 4.

Complex structures detected in the IMF also arise due to spatial variations across the solar surface of the plasma ejection. A fast plasma stream, ejected radially from the solar surface, interacts in interplanetary space with a slower stream ahead of it, causing a shock boundary to form between the streams. At the shock the field and plasma is compressed and a turbulent region of compressed solar wind is produced between the shock and the fast stream interface. Fast streams are probably correlated with increased geomagnetic activity (Snyder et al., 1963).

The plasma parameters and flow speed at Earth orbit, summarised in Table 1.1, mean that the plasma is collisionless (mean free path ~ 1 A.U.), highly conducting, and supersonic. The magnetic field strength measurements show the flow to be super-Alfvénic also. The energy density of the plasma generally exceeds that of the magnetic field by up to a factor of 10. These properties have important implications when we consider the interaction of the solar wind with a planetary obstacle.

The first approximation to the interaction of the solar wind with the terrestrial environment has already been discussed, namely the formation of the Chapman-Ferraro current sheet and the magnetospheric cavity within which the Earth's field is dominant and the solar wind is excluded.

The situation is complicated, however, because the solar wind is supersonic. A shock wave forms because information about the obstacle cannot propagate upstream fast enough to modulate the oncoming flow in a continuous manner. The Earth's bow shock is situated generally 2-3 R_E upstream of the dayside magnetopause which is itself typically located at a geocentric distance of 10-15 R_E . These two boundaries enclose a turbulent region of plasma called the magnetosheath. Here the solar wind flow is deflected and slowed around the obstacle. The loss of directional kinetic energy of the plasma as it crosses the bow shock is deposited into its thermal energy so that the magnetosheath temperatures are $\sim 5 \times 10^6$ °K, up to an order of magnitude higher than in the solar wind. The slowing of the flow also means that the magnetic field is compressed across the shock by a factor of up to 4, depending on the solar wind field orientation with respect to the shock normal. At the nose of the magnetopause the flow stagnates and temperature, density and (usually) field maximise. The change in plasma properties across the shock all combine to create a region of subsonic flow.

Despite the solar wind being a magnetofluid, the flow around the magnetosphere is in fact very close to that of a supersonic ideal gas around an obstacle e.g. air flow around a rifle bullet. The reason for this is that the energy density of the solar wind flow is greatly in excess of that of the IMF. Thus the magnetic terms in the momentum and energy equations of the interaction can, to a first approximation, be neglected. The magnetic field then acts as a fluid tracer, being draped around the obstacle as it convects with the local flow speed in accordance with the "frozen-in" field theorem.

Using this approximation Spreiter and Stahara (1980) have produced maps of the spatial distribution of plasma parameters and bow shock location assuming a rigid magnetospheric obstacle and for a given solar wind Mach number. Fig. 1.3 is a composite of a part of their results showing the velocity contours and streamlines around a rotationally symmetric magnetosphere with a solar wind Mach number = 8.0. The deflection and slowing of the flow in the magnetosheath is clearly seen.

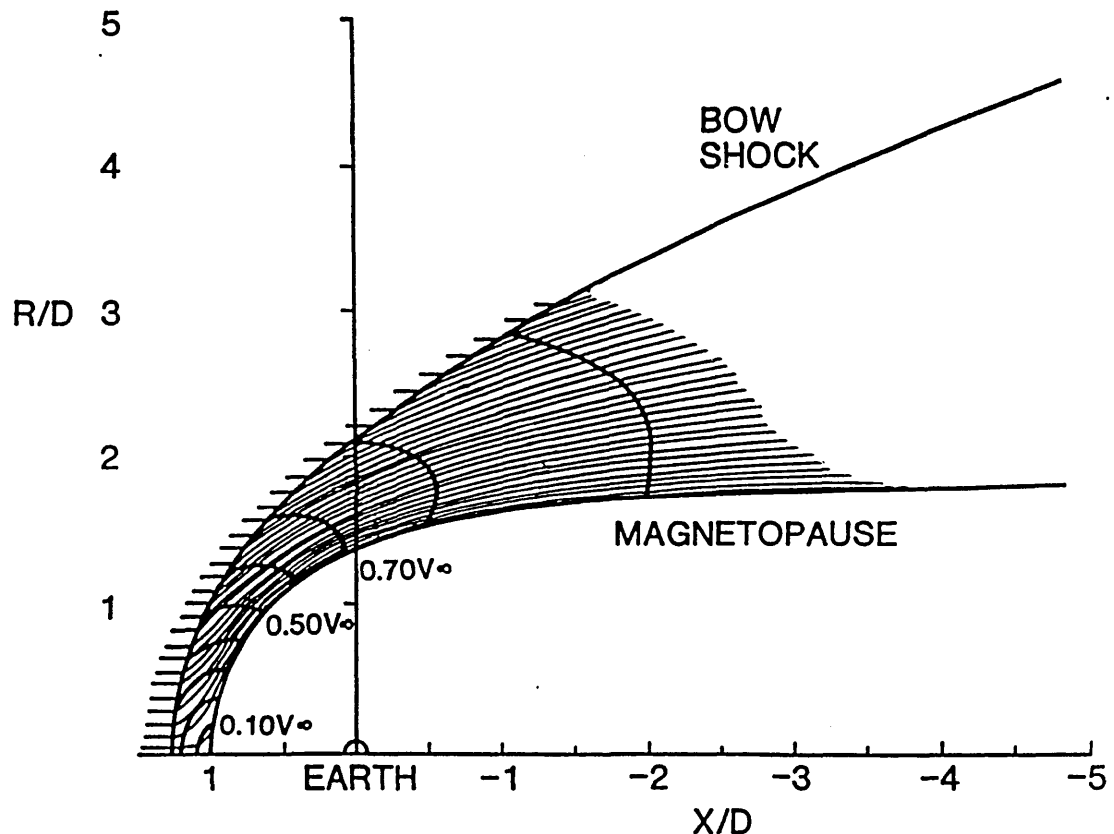


Fig. 1.3. Gas-dynamic model of the magnetosheath velocity field (Spreiter and Stahara, 1980). The figure is a cut through the volume of revolution of the modelled magnetosheath. The light lines are flow streamlines and the heavy lines are contours of constant velocity, normalised to the solar wind speed, V_∞ . Spatial scales are normalised to the subsolar magnetopause stand-off distance, D . The case is appropriate for a solar wind Mach number of 8.0 and specific heat ratio of $5/3$.

1.3. Magnetospheric Convection.

Although the solar wind flow and magnetic field are excluded from the magnetospheric cavity, their influence extends well within it. The inner magnetosphere within 4-6 R_E has an essentially dipolar magnetic field and the plasma and field co-rotate with the Earth. However, the field in the outer magnetosphere is distorted and here plasma and field move in a different manner.

Experimental evidence of magnetospheric convection came initially from mid- and high-latitude ground magnetometers. The recorded perturbations in the geomagnetic field were employed to infer an ionospheric current system, called the Solar Polar Quiet (S^P_q) current system. Currents arise due to a relative motion of ions and electrons. In the ionosphere the presence of neutral particles means that ions are no longer frozen to the magnetic field, but suffer a drag force due to ion-neutral collisions. However, the small electron collision cross-section means that the electrons are still free to convect with the field. Therefore the S^P_q currents can be explained by a field line motion anti-parallel to the current vector. Projecting the inferred field line motion into the magnetosphere, a convection pattern results in which plasma and field are convected anti-sunward over the poles and returned sunward at lower latitudes.

Axford and Hines (1961) proposed that the energy for this circulation came from a viscous interaction, analogous to friction, between the solar wind flow and the magnetosphere. In their model the magnetosphere resembled a falling raindrop where the external flow exerts a frictional force which transfers momentum to the fluid in the outer regions of the drop. The fluid element swept back with the external flow is subsequently returned inside the drop. Fig. 1.4 shows the magnetospheric circulation in the equatorial plane due to such a viscous interaction. Although the magnetospheric circulation was described well by this model, the nature of the viscous force in a collisionless plasma was problematic.

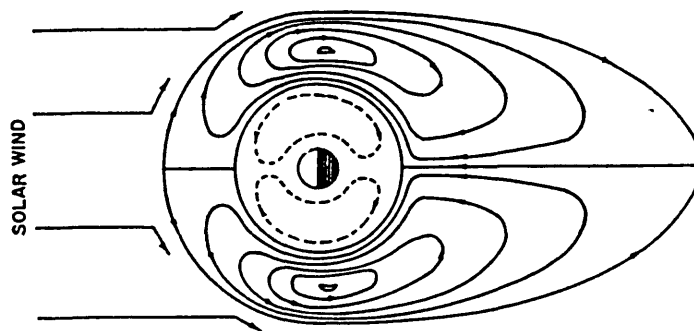


Fig. 1.4. Flow streamlines in the magnetospheric equatorial plane due to momentum transfer from the solar wind by a viscous interaction at the magnetospheric boundary (after Axford and Hines, 1961).

An alternative model was proposed by Dungey (1961). This invoked the mechanism of "magnetic reconnection". Fig. 1.5 shows the envisaged magnetospheric field topology in the noon-midnight meridian plane when the IMF is (a) southward, and (b) northward. In the latter case little or no magnetic interaction is expected to take place on the dayside between the IMF and the geomagnetic field; the magnetosphere forms a Chapman-Ferraro-like cavity in the solar wind.

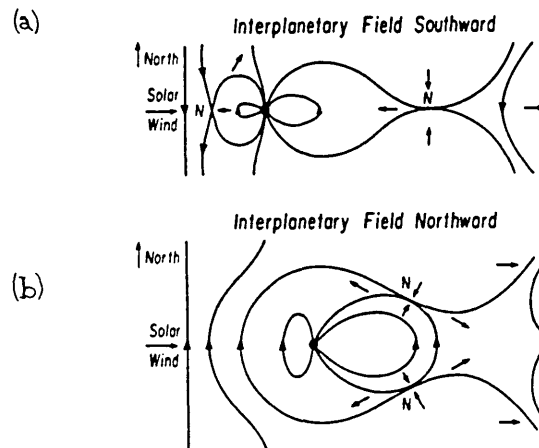


Fig. 1.5. Dungey's model of the magnetosphere for the two cases of a southward and a northward directed IMF. Magnetic neutral points at which reconnection may take place are indicated by the letter N. Plasma flow is indicated by the arrows. The diagrams are illustrative and not to scale (from Dungey, 1963).

In case (a) the component of the IMF anti-parallel to the geomagnetic field means that a magnetic neutral line is present in the equatorial plane at the dayside magnetopause. In this region the "frozen-in" field approximation breaks down and magnetic diffusion dominates. In the steady state, the magnetic diffusion is supported by magnetic flux transport into the diffusion region from outside. Thus, on either side of the diffusion region magnetic field lines converge towards the neutral line carrying plasma with them. The plasma inflow is balanced by an ejection of accelerated plasma away from the neutral line along the boundary. The outflow is achieved by allowing the merging solar wind and terrestrial magnetic field lines to break and reconnect with each other at the "X-type" separatrix shown. The reconnected field lines have a small field component threading the magnetopause and are highly curved. The associated field tension accelerates plasma and field along the boundary away from the diffusion region. In this way electro-magnetic energy is extracted from the solar wind and converted into plasma energy on field lines connected to the Earth.

The process of magnetic reconnection at the dayside magnetosphere creates two classes of geomagnetic field lines. "Open" geomagnetic field lines have one end connected to the

IMF and the other end maps to the high-latitude ionosphere, known as the polar cap. "Closed" field lines have both ends in the ionosphere at lower latitudes.

Open field lines move under the influence of the solar wind flow. At high latitudes field and plasma are transported in an anti-sunward direction over the poles. The field lines are swept well beyond the Earth and extend to form a long magnetotail. The tail comprises two lobes of oppositely directed open field lines separated by a current sheet. As at the dayside magnetopause a neutral line forms, at any point between $\sim 40 R_E$ and $1000 R_E$ downstream. Magnetic field lines from the northern and southern lobes reconnect. Plasma is accelerated down the tail into the solar wind on a re-formed interplanetary magnetic field line. On the earthward side a highly distended closed field line is formed, whose magnetic tension accelerates plasma and field toward the dayside around the Earth, thereby completing the magnetospheric circulation.

Thus the two models, viscous and magnetic reconnection, both successfully describe the gross magnetospheric circulation. Over the succeeding ~ 25 years observations have provided evidence for both mechanisms to be at work and Cowley (1982) has suggested how they might co-exist. The strength of the magnetospheric circulation can be parameterised by the electric potential across the polar cap in the dawn-dusk plane. This is a direct measure of the rate of magnetic flux transport from the dayside to the nightside. A typical value is 60 kV, but this figure can vary greatly ($\sim 40 - 200$ kV) reflecting the changing efficiency of the solar wind - magnetosphere coupling. Using polar orbiting spacecraft several workers (Reiff et al., 1981; Doyle and Burke, 1983; Wygant et al., 1983) have shown that the cross-cap potential depends strongly on the north-south component of the IMF. This implies that reconnection, whose rate is expected to increase with southward IMF, drives much of the magnetospheric convection. Wygant et al. attempted to determine from their results the size of any residual cross-cap potential in the absence of reconnection. They estimated this to be ~ 10 kV. Thus we can conclude that reconnection, when it operates, is the dominant mechanism of momentum transfer to the magnetosphere.

1.4. Magnetosphere-Ionosphere Coupling.

We have already mentioned how the magnetospheric circulation is observable at ionospheric heights by the current system it creates there. We shall now consider how the magnetospheric system couples to its lower boundary.

On magnetospheric scales the ionosphere may be regarded as a thin resistive boundary around the Earth's surface. Its resistivity arises from the large number of neutrals relative to ions existing at ionospheric heights (~ 100-1000 km). At 140 km, at the base of what is known as the F region ionosphere, the ion-neutral collision frequency is approximately equal to the ion gyrofrequency. Thus, below this height, in the E region ionosphere, ion motion is no longer ordered by the magnetic field. The electrons, however, do not experience a drag force due to neutral collisions. The difference in electron and ion mobility gives rise to an anisotropic conductivity perpendicular to the field. In the direction of the driving force, usually the magnetospheric electric field, E , the conductivity is known as the Pedersen conductivity. The Hall conductivity is that in the $E \times B$ direction. In general, the ionospheric conductivity may be expressed as a tensor quantity, σ , such that:

$$\mathbf{j} = \nabla \cdot \sigma \mathbf{E} \quad (1.2)$$

where, in the absence of vertical currents ($j_z = 0$) due to the large field-aligned (direct) conductivity, the field perpendicular currents (j_x, j_y) are given by:

$$\begin{pmatrix} j_x \\ j_y \end{pmatrix} = \begin{pmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{yx} & \sigma_{yy} \end{pmatrix} \begin{pmatrix} E_x \\ E_y \end{pmatrix} \quad (1.3)$$

For a magnetic field at an angle of dip, I , the tensor elements are:

$$\sigma_{xx} = \frac{\sigma_0 \cdot \sigma_1}{\sigma_0 \cdot \sin^2 I + \sigma_1 \cdot \cos^2 I} \quad (1.4)$$

$$\sigma_{xy} = -\sigma_{yx} = \frac{\sigma_0 \cdot \sigma_2 \cdot \sin I}{\sigma_0 \cdot \sin^2 I + \sigma_1 \cdot \cos^2 I} \quad (1.5)$$

$$\sigma_{yy} = \frac{\sigma_2^2 \cdot \cos^2 I}{\sigma_0 \cdot \sin^2 I + \sigma_1 \cdot \cos^2 I} + \sigma_1 \quad (1.6)$$

where $\sigma_0, \sigma_1, \sigma_2$ are the direct, Pedersen, and Hall conductivities respectively.

In the steady state, magnetospheric field lines are electric equipotentials and so the convection electric field driven by the solar wind-magnetosphere interaction is mapped down

to ionospheric heights. Here the electric field drives the plasma motion and field-perpendicular currents flow.

The Pedersen currents flowing in the ionosphere constitute an energy sink to the magnetospheric convection i.e. $\mathbf{j}_p \cdot \mathbf{E} > 0$. The drag force exerted by the neutrals on the ionospheric end of a moving field line causes it to tilt such that its magnetic stress just balances the drag force. The stress is communicated along the field line by the Alfvén wave mode carrying field-aligned currents which close the Pedersen currents. This model is discussed

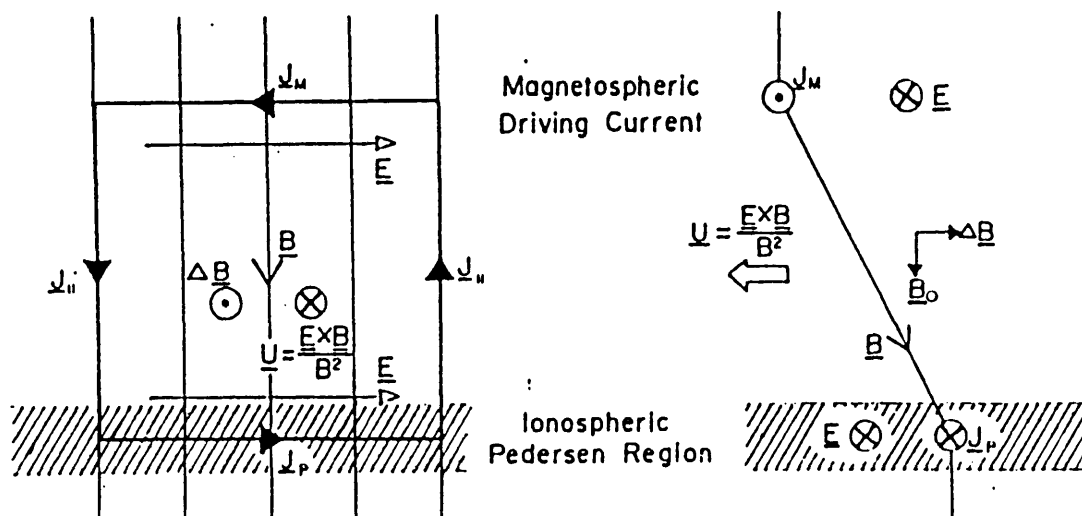


Fig. 1.6. An idealised model of the field-aligned currents required to couple magnetospheric flow to the ionosphere. Geomagnetic field lines tilt in the direction of motion to provide a magnetic tension force to overcome the ionospheric drag (from Southwood and Hughes, 1983).

by Southwood and Hughes (1983) and is shown in Fig. 1.6. Field-aligned currents can also be driven by gradients in the Pedersen conductivity.

The electric field also generates Hall currents anti-parallel to the $\mathbf{E} \times \mathbf{B}$ drift. In steady state the ionospheric flow is incompressible and so in a uniform conductivity ionosphere the Hall currents are divergence-free. Gradients in the Hall conductivity will tend to alter the steady state flow such that it avoids flowing across such gradients. To a good approximation, it is the Hall currents alone that perturb the geomagnetic field at the Earth's surface, as was assumed in the interpretation of the S^P_q current system. The field-aligned and Pedersen currents shield each other from the region below the ionosphere (Fukushima, 1969). We shall use this fact in analysing ground magnetometer data in Chapter 4.

In summary, mapping of the magnetospheric convection electric field to ionospheric heights yields the global current systems shown in Fig. 1.7. The flow (Hall current) shear

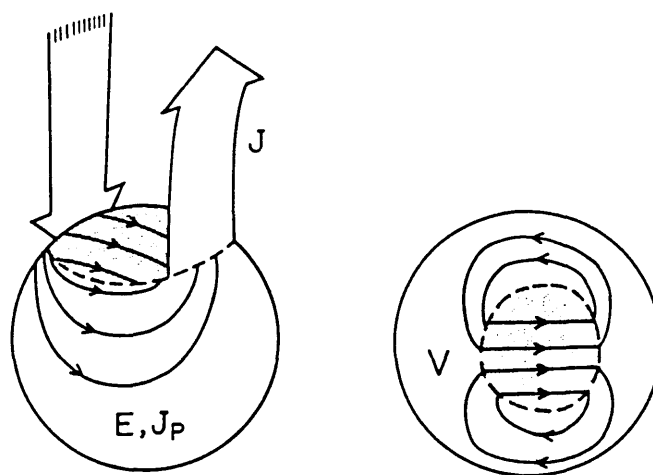


Fig. 1.7. The electric field or Pedersen current pattern (left) associated with the two-cell ionospheric convection pattern (right). At the polar cap boundary (dashed line) the flow shear requires the presence of field-aligned Region I "driving" currents to feed the concomitant divergent Pedersen currents at dawn and dusk (from Vasyliunas, 1975).

across the polar cap boundary at dawn and dusk marks a divergence of electric field and Pedersen current. Thus in these two regions are present field-aligned current sheets, upward at dusk and downward at dawn; these are known as the Region I currents. They have been termed the "driving currents" (Vasyliunas, 1975; and references therein) because of their direct relationship to the strength of the magnetospheric circulation.

At lower latitudes another current is present called the Region II current system (not shown in Fig. 1.7). This has the effect of shielding the convection electric field from the near-Earth magnetosphere. The field-aligned currents are generated to prevent plasma compression on earthward moving flux tubes, which is energetically expensive. In Chapter 5 we shall present ground radar data which we interpret to be a direct observation of the Region II current sheet in the mid-afternoon sector.

The two principal current systems have been observed by polar orbiting spacecraft. Magnetic field perturbations in the auroral zone region were interpreted by Armstrong and Zmuda (1970) as showing the presence of oppositely directed field-aligned currents separated in latitude. Statistical distributions of these currents have been derived by Iijima and Potemra (1978) and are shown in Fig. 1.8, which compares favourably with the field-aligned current systems shown in Fig. 1.7.

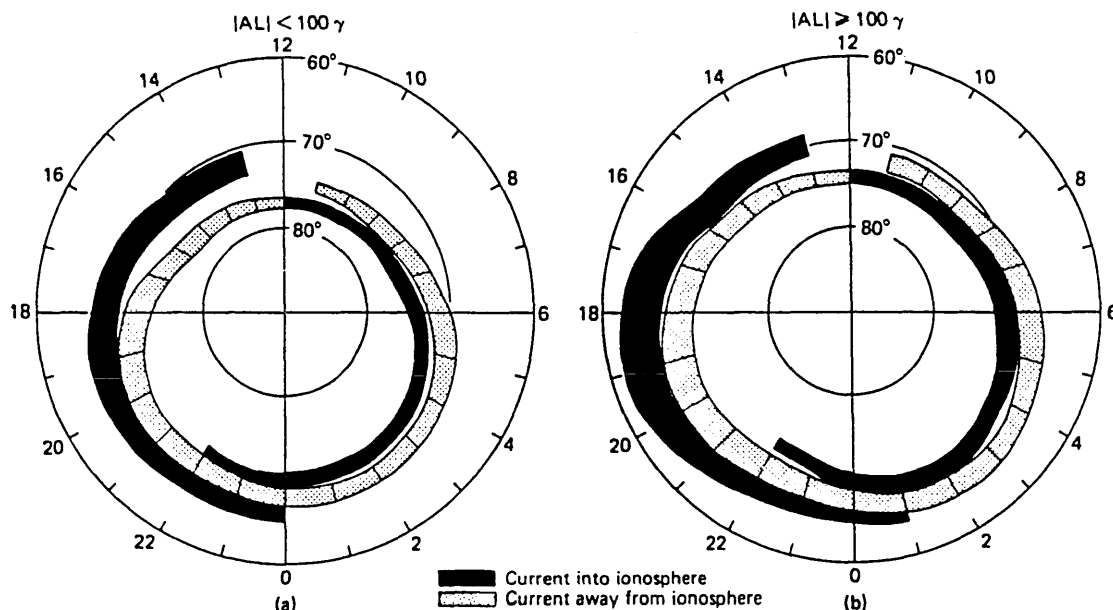


Fig. 1.8. The distribution and polarity of large-scale field-aligned currents at high geomagnetic latitudes determined from polar-orbiting satellite magnetometer data. Approximately 400 polar passes were used to map the current distribution during weakly disturbed conditions ($AL < 100$ nT; left hand figure), and during active periods ($AL > 100$ nT; right hand figure) (from Iijima and Potemra, 1978).

1.5. The Magnetospheric Substorm.

In the above discussion we have assumed a steady state model of magnetospheric convection. However, this situation hardly ever prevails. The strongest evidence for the imbalance between anti-solar flux transport and its return to the dayside is the magnetospheric substorm. Observations have shown a characteristic magnetospheric response sequence to solar wind energy input, known as the phases of a substorm (McPherron et al., 1973). The sequence of events in the Earth's magnetic tail is illustrated in Fig. 1.9.

The sequence begins with the growth phase. Reconnection at the dayside magnetopause opens geomagnetic field lines and transports dayside magnetic flux and plasma to the tail. The tail lobe field is observed to increase (e.g. Fairfield and Ness, 1970) and the plasma sheet thin (e.g. Hones et al., 1967) as more open flux is transported to the nightside, whilst the dayside magnetosphere erodes due to the corresponding loss of closed flux (Aubry et al., 1970). At ionospheric heights the increase in open flux means that the polar cap grows (as the field strength here is constant) and the auroral zones move equatorward. The ionospheric flow pattern during the substorm growth phase, when dayside reconnection is dominant, has been modelled by Siscoe and Huang (1985).

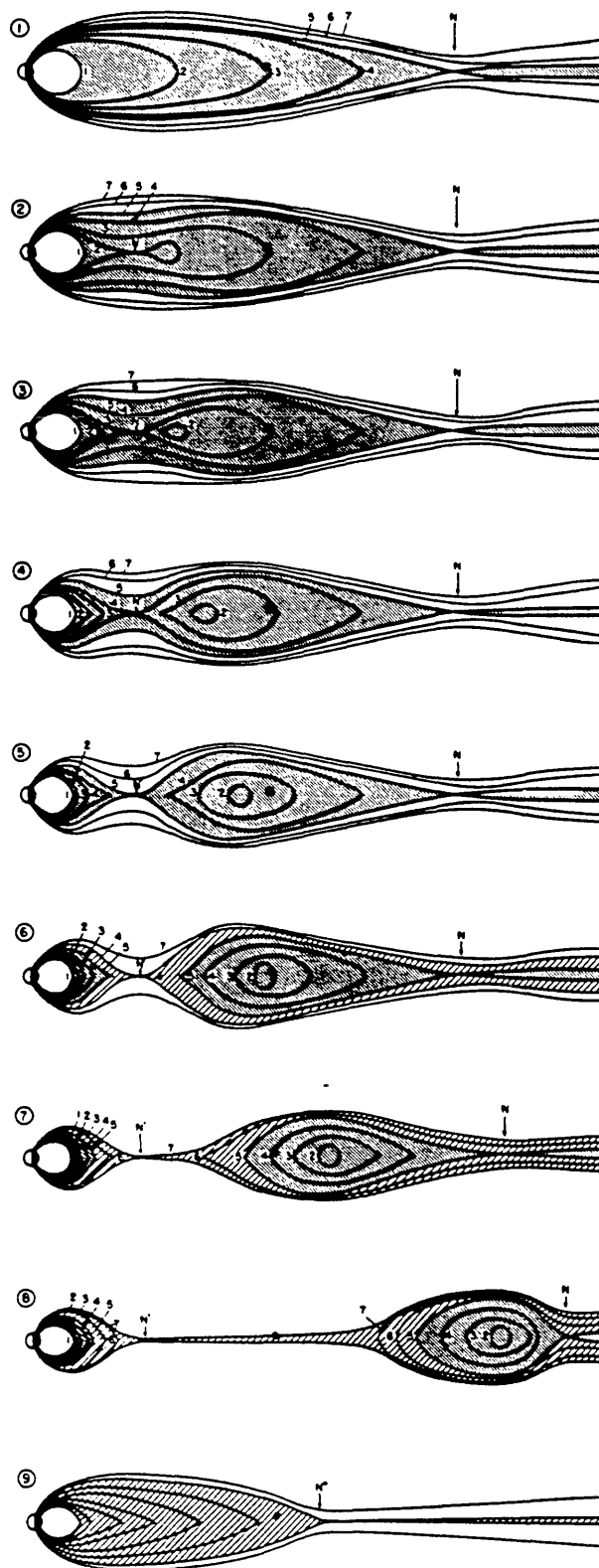


Fig. 1.9. Time sequence of changes in the magnetic field and plasma in the Earth's magnetic tail during a substorm. Pre- and post substorm neutral lines are denoted by N and N', respectively. The temporal evolution of seven field lines is indicated during the growth phase (panel 1), the expansion phase (panels 2-7), and the recovery phase (panels 8-9) (from Hones, 1977).

After some time the tail responds to the dayside reconnection in an explosive manner, known as substorm onset. A neutral line forms in the near-Earth tail ejecting energetic plasma both downstream (e.g. Nishida and Lyon, 1972) and earthward (e.g. Parks and Winckler, 1968). The tail field becomes more dipolar (e.g. Cummings et al., 1968) and particles are accelerated to high energies, increasing the ring current strength (e.g. Frank, 1970). In the ionosphere is seen a strong westward electrojet in a localised sector near midnight (e.g. Akasofu and Meng, 1969) which arises from the short-circuiting through the ionosphere of the cross-tail current which supported the tail-like field (e.g. McPherron et al., 1973). Temporal variations in this solenoidal current system give rise to Pi 2 ground magnetic oscillations (Lester et al., 1984). The dominant nightside reconnection returns flux and plasma to the dayside, causing the polar cap to rapidly contract and the aurora to move poleward (Akasofu, 1964) and expand longitudinally (Sergeev and Yahnin, 1979). This period in the substorm history is called the expansion phase.

The final stage in the substorm sequence is the recovery phase. During this period the near-Earth neutral line migrates anti-sunward and the ring current diminishes.

In general, the unsteady behaviour of the magnetospheric system is due to two causes, though the precise nature of the system response is in dispute. The first cause is the variability of the momentum input on the dayside due to unsteady solar wind conditions. Reconnection at the dayside magnetopause has been observed to take place both in an impulsive manner, as evidenced by flux transfer events (Russell and Elphic, 1978), but also in a quasi-steady way (Sonnerup et al., 1981; Paschmann et al., 1986).

The second, more controversial, effect is the response of the Earth's magnetotail to the build-up of nightside magnetic flux following dayside reconnection. The two competing models of the magnetospheric response to solar wind momentum transfer are attributable to Akasofu (1980) and McPherron et al. (1973).

In the Akasofu model it is assumed that the solar wind energy input modulates proportionately the energy output associated with the magnetospheric return flow to the dayside i.e. the magnetospheric response is directly driven by the solar wind. Thus, if the dayside energy input is steady, then the response is also steady. Erosion and the polar cap expansion occur because there is a lag associated with the transfer of magnetic flux from the dayside to the tail. However, this model would not predict the sudden substorm onset under steady solar wind input conditions, but would require them to change suddenly.

The McPherron model assumes some "trigger" to exist which is a characteristic of the magnetotail. The flux in the tail can increase steadily and the plasma sheet thin until the tail current suddenly collapses and is shorted across the ionosphere to produce the sub-

storm current wedge. The diversion of the tail current can be explained by the formation of a neutral line and magnetic reconnection. This means that there must be a sudden decrease in the current sheet conductivity to form the neutral line.

The generally large variability in the solar wind over substorm time scales ($\sim 0.5 - 2$ hours) means that it is difficult to establish which model is the more accurate description of the magnetospheric system. In Chapter 4 we shall study a substorm sequence and discuss its behaviour.

It is hoped that this thesis will demonstrate to the reader that the solar wind-magnetosphere-ionosphere interaction is fundamentally a time-dependent problem. To understand the system behaviour it is important to know how information is communicated within it, and thus coordinated observations throughout the system are vital. In Chapters 3, 4, and 5 multi-point measurements complement each other and afford us a better understanding of the physics behind single station observations of (e.g.) ionospheric phenomena.

CHAPTER 2

A MODEL OF QUASI-STEADY IONOSPHERIC CONVECTION AND EVIDENCE FOR TIME-DEPENDENT PHENOMENA.

2.1. Preface.

Sections of this chapter have been published previously (Freeman and Southwood, 1988a). The work has been extended to provide a simple model for the interpretation of the steady state diurnal ionospheric flow variation measured by the SABRE radar, and for understanding departures from it. Two models for the case of time-dependent magnetospheric erosion are presented and discussed. A comparison of their ionospheric effect has led to a re-interpretation of the SABRE data from September 4, 1984 from that discussed in Freeman and Southwood (1988a). The subsequent acquisition of ancillary data sets indicates that the polar cap expansion associated with the inferred magnetospheric erosion maintains the essentially circular polar cap geometry, rather than distorting the dayside polar cap as originally proposed. The event is analysed in Chapter 4 and has highlighted for us the merits of multi-instrument studies. Though one model provides a better description of this individual event, both models are discussed as the alternative remains a valid physical model but is likely to prevail under different geophysical conditions, perhaps during particularly dynamic events such as the substorm expansion phase.

2.2. Introduction.

In this chapter we describe simple quasi-global models of ionospheric flow to aid the interpretation of dayside ionospheric radar scatter data. We compare our model results with examples of dayside flows observed by the SABRE bistatic coherent radar facility. We use a very simple computational model in which many effects (such as ring current shielding, non-uniformity of ionospheric conductivity) have been omitted. Although undoubtedly present in reality, the effects have been omitted in order to ease interpretation. In particular, we aim to elucidate the potential signatures of magnetopause erosion and allied phenomena at ionospheric heights. Erosion implies the addition of magnetic flux to the polar cap and consequently a reduction in the latitude of the polar cap boundary. We consider here the possibility of both localised erosion over part of the dayside and the case of an isotropic polar cap expansion.

2.2.1. Preliminary discussion.

In Chapter 1 we discussed the control of magnetospheric plasma by the solar wind. The observed large scale magnetospheric convection system requires the transfer of momentum from the solar wind to the magnetosphere, either through viscous drag (Axford and Hines, 1961) or by magnetic reconnection (Dungey, 1961). The latter process appears to be dominant, at least when the interplanetary magnetic field (IMF) has a southward component (Cowley, 1982). Newly-opened dayside field lines drive polar cap plasma in a generally anti-sunward direction due to the action of magnetic tension and the kinetic pres-

sure of the flowing magnetosheath plasma. Continuity then demands a return plasma flow on closed field lines giving rise to the well known twin cell circulation pattern.

In the open field line region in steady state, the connected field imposes an electric potential around the polar cap boundary in the ionosphere which serves to determine the pattern of return flow in the closed field line region. The convection electric field also drives Pedersen currents in the ionosphere because of ion-neutral collisions. The field-aligned (Birkeland) currents which feed the ionospheric Pedersen currents (Vasyliunas, 1975 and references therein) flow in and out of the ionosphere only at the polar cap boundary in the simplest picture, forming the Region I current system described in Chapter 1. The position of the boundary itself is determined by the overall stresses on the magnetosphere and does not change in the steady state.

The classical picture has been extended using empirical models (e.g. Heppner and Maynard, 1987; Heelis, 1984). These confirm the basic two-cell pattern but show added complexities. In the models of Heppner and Maynard equipotentials cross the polar cap boundary at all dayside magnetic local times. However, in the work of Heelis and Hanson (1976) a narrow throat is present near local noon across which most ionospheric plasma crosses into the polar cap. The "throat" would arise from localised reconnection at the dayside magnetopause near noon. If reconnection took place across a greater portion of the dayside magnetopause then the situation would appear more like that due to Heppner and Maynard. One purpose of this chapter is to examine the effects of localised reconnection on flow patterns but also to look at the effects of actual motion of the polar cap boundary itself.

Spacecraft measurements often reveal highly time-dependent field and plasma behaviour in the vicinity of the magnetopause itself. Reconnection appears to occur in a patchy manner as evidenced by flux transfer events (FTEs) (Russell and Elphic, 1978; Rijnbeek et al., 1984; Berchem and Russell, 1984; Southwood et al., 1986). A flux transfer event, if interpreted with the Russell and Elphic model or developments of it, is an example of erosion on a small spatial scale (Southwood, 1987). However, as illustrated by Aubry et al. (1970) and Paschmann et al. (1986) spacecraft have been found at times to stay at the magnetopause for extended periods of up to 30 minutes, moving thousands of kilometers earthwards, whilst the solar wind pressure remains constant. In the Paschmann et al. report reconnection is known to be ongoing through the period. In all of these cases magnetopause erosion is likely to be taking place, wherein there is a net transfer of magnetic flux from the dayside closed field line region into the polar cap and tail lobes. The erosion of the magnetosphere by magnetic reconnection is also implied in statistical studies of the magnetopause boundary position as determined from spacecraft observations. It is

found that the magnetospheric topology is determined primarily by pressure balance with the oncoming solar wind. However, after normalising the boundary location to the prevailing solar wind dynamic pressure, it is found that a weaker dependence of the magnetopause position on the north-south component of the IMF also exists such that the subsolar magnetopause is found closer to the Earth, and the polar magnetopause region is found further away from the Earth, during times of southward IMF (Fairfield, 1971; Formisano et al., 1979). This result supports the argument that magnetic flux is eroded from the dayside magnetosphere and added to the tail whenever the IMF has a component anti-parallel to the geomagnetic field, a condition propitious for reconnection at the dayside magnetopause.

In this chapter we ask what possible signatures could be found in the ionosphere during periods when the magnetopause is eroding. We shall retain the term polar cap boundary to mean the demarcation line between the regions of open and closed field lines in the ionosphere. As dayside erosion takes place the amount of open flux increases and, as the polar cap field remains effectively constant, so the polar cap area must grow. In the absence of balancing nightside reconnection we expect that the polar cap boundary moves equatorward. We shall consider two possible ways in which the magnetosphere and its ionospheric projection may deform.

Siscoe and Huang (1985) have modelled the case of uniform polar cap expansion. In their example they consider a nett transport of magnetic flux into the polar cap over a limited local time sector on the dayside, the "throat". They impose that the concomitant polar cap expansion is at a uniform rate at all local times. Thus, away from the reconnection throat where flow is poleward into the polar cap, the plasma at the polar cap boundary moves at the velocity of the boundary. In this way the feet of closed field lines are displaced equatorward and sunward to accommodate the polar cap growth. The scenario is sketched in Fig. 2.1a where it can be seen that the resultant ionospheric convection pattern remains essentially a twin-cell circulation, but where the flow strength is strongest in the vicinity of the reconnection throat on the dayside. The situation may be extended to the case of dominant nightside reconnection (Fig. 2.1b) where the polar cap contracts and flow is strongest on the nightside, or generalised to some intermediate reconnection rate imbalance, approaching the steady state condition (Fig. 2.1c).

Studies have been done to correlate polar cap boundary position with interplanetary and geomagnetic parameters during disturbed times (e.g. Meng, 1983; Rodger and Broom, 1986). Much of this work assumed that the polar cap boundary moves equatorward uniformly over all local times. In some average sense this must be so but the time scale for uniformity to be established is not known. If the reconnection rate is enhanced on a time scale

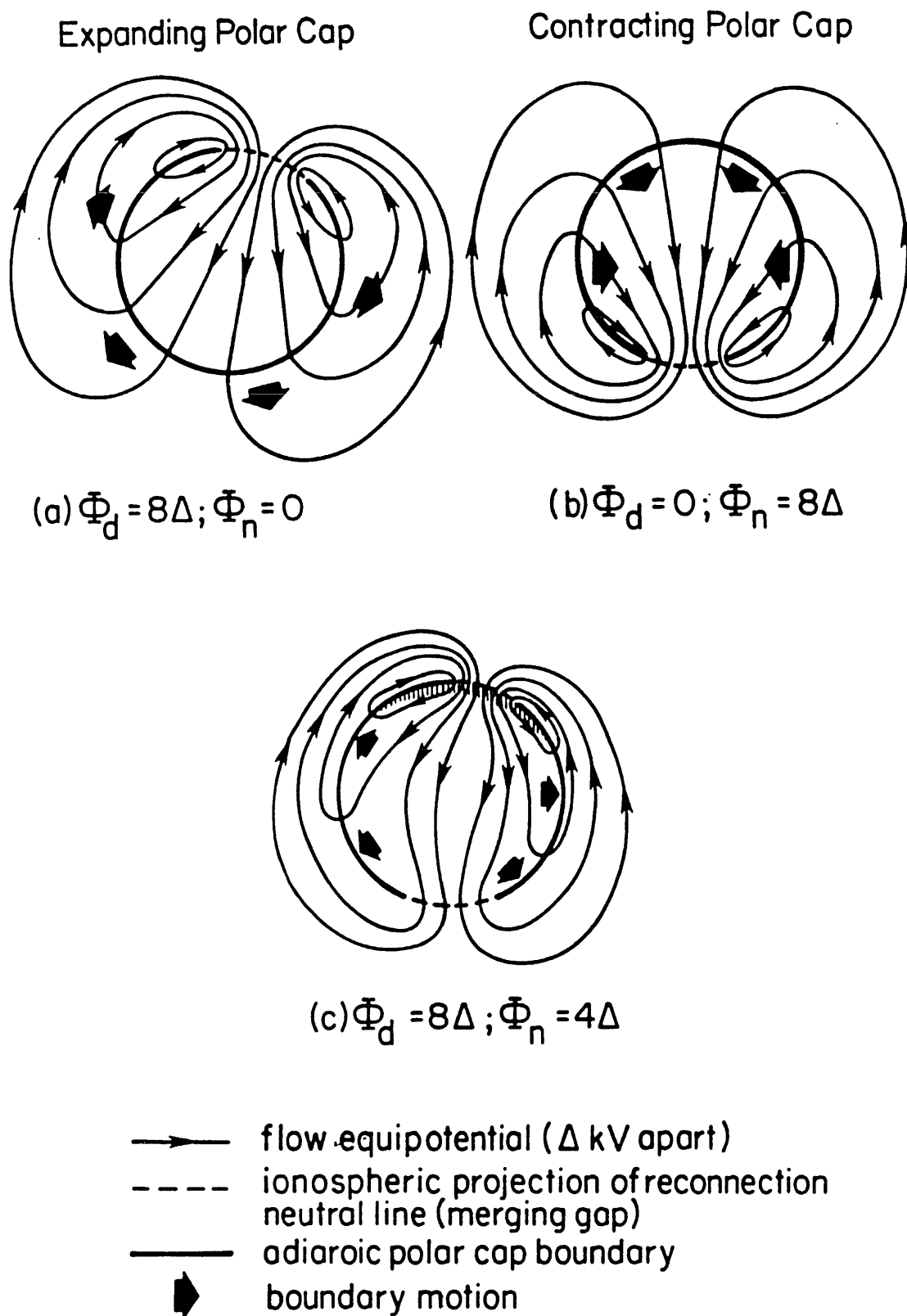


Fig. 2.1. Sketches of the modified two cell ionospheric convection pattern due to (a) dayside reconnection alone, (b) nightside reconnection alone, and (c) concurrent, but unbalanced, dayside and nightside reconnection with the dayside reconnection rate dominant (from Lockwood et al., 1989a).

shorter than the time scale for the ionospheric plasma to be set in motion then the electric field at ionospheric heights will be small. In this case the electric field is no longer a potential field because the induction field is dominant, associated with the changing magnetospheric topology. Thus, in the case of spatially localised, time dependent reconnection (FTE's) it seems very unlikely that the cap expands uniformly over all local times.

Theoretical studies of the effect of magnetopause erosion on the magnetosphere-ionosphere system are few. Coroniti and Kennel (1972, 1973) followed up the observational work of Aubry et al. (1970) and discussed the distortion of the magnetospheric cavity in the substorm growth phase. They proposed that the ionospheric Pedersen conductivity may play a role in exerting a sufficient drag on the field lines at low altitude that the electrostatic convection electric field is less than the reconnection electric field leading to magnetospheric erosion. However, they did not discuss the explicit effect on ionospheric flow patterns that we take up in this chapter. If magnetospheric erosion is localised along the dayside magnetopause due to a spatially limited neutral line then the resultant magnetopause boundary deformation would map to a localised bulge appended to the dayside polar cap. In this case the bulge would grow on the long (tens of minutes) time scale of the substorm growth phase, unless the localised distortion of the magnetospheric cavity could not be sustained.

Hence, if reconnection takes place over some localised extent of the dayside magnetopause, but the associated plasma transport is hindered, then equatorward bulges in the polar cap boundary of various scale sizes may occur in the ionosphere. Recently there has been increasing evidence for the irregular nature of plasma transfer across the magnetopause, both temporally and spatially, from ionospheric observations (Sandholt et al., 1986). The ionospheric footprints for these events indicate scale sizes ranging from hundreds to greater than a thousand kilometers. On the small scale these events are likely to be due to FTE's (Southwood, 1987) and recent multi-instrument studies have supported this interpretation (Lockwood et al., 1989b). But note that occasionally FTE footprints can be extensive; in Paschmann et al.'s (1986) study on September 4, 1984 when the magnetosphere was highly compressed two FTE's were observed in the IRM spacecraft data (his figure 2). Using Southwood's arguments these would enclose magnetic fluxes of order 4×10^7 Wb and thus could subtend an area of order 10^6 km² in the ionosphere. Additionally, the recent interpretation of FTEs as local bulges in the dayside magnetopause reconnection wedge arising from a fluctuation in a pre-existing reconnection rate (Biernat et al., 1989; Southwood et al., 1988) means that the events may be extended in local time, and hence contain more magnetic flux, than that envisaged in the Russell and Elphic model.

Let us now consider the time evolution of a dayside polar cap boundary bulge in the ionosphere. Fig. 2.2a shows two possible cases. In each case a bulge has been formed by erosion but there is a background ionospheric flow sustained by reconnection occurring over some fixed range of local time. The figures indicate that the background flow can control the evolution of a bulge. In case (I) the flow is driving ionospheric plasma polewards and spreading dawn- and dusk-wards to distribute itself more evenly in the interior polar cap as shown. As a result the boundary bulge thus spreads in local time although the reconnection site may remain in the same position. Case (II) might occur if the newly opened flux is driven polewards and duskwards, as expected when IMF B_y is negative (Cowley, 1981). An asymmetrical bulge would develop as sketched as the flow continued with continued reconnection occurring in the same position. If B_y were positive then the flow is skewed in the opposite sense. These qualitative results have been supported by an idealised quantitative model of the plasma dynamics close to the polar cap boundary (Lockwood and Freeman, 1989). An important conceptual principle is illustrated by the above discussion, namely that, although dayside reconnection can move the polar cap boundary equatorward without plasma motion equatorward in this region, if the dayside boundary moves poleward, then it must have poleward plasma motion associated with it.

There is no reason to believe that magnetospheric erosion, limited or otherwise, may not last for extended periods. The OGO 5 (Aubry et al., 1970) and IRM (Paschmann et al., 1986) reports show that erosion may occur for periods of order at least half an hour. Magnetic stress would build up in the geomagnetic tail as the solar wind stretches the polar cap field. The wholesale release of stress in the system might be accomplished by the occurrence of a substorm on the nightside. This substorm sequence is examined and confirmed in Chapter 4, using concurrent observations in space and on the ground. In the example presented there the dayside magnetospheric erosion is best approximated at ionospheric heights by the uniform polar cap expansion envisaged by Siscoe and Huang (1985).

The arguments presented above may be extended to other situations. Apart from dayside events associated with FTEs (e.g. Lockwood and Smith, 1989), observations of the auroral oval using DMSP data indicate that a poleward bulge of Gaussian cross-section into the polar cap is sometimes seen on the nightside (Holzworth and Meng, 1975). In addition, observations by the SABRE radar (M. Lester, private communication) have shown a poleward and sunward propagation across the radar field of view in the early morning MLT sector of a convection reversal boundary which is skewed at a large angle to a L-shell. This could be interpreted as the relaxation of a locally distorted polar cap boundary (such as observed by Holzworth and Meng), as is envisaged in case (iii) below but this time applied to the nightside. The scenario has been proposed to occur at substorm onset by Akasofu (1977) from observations of auroral arcs and is sketched in Fig. 2.2b.

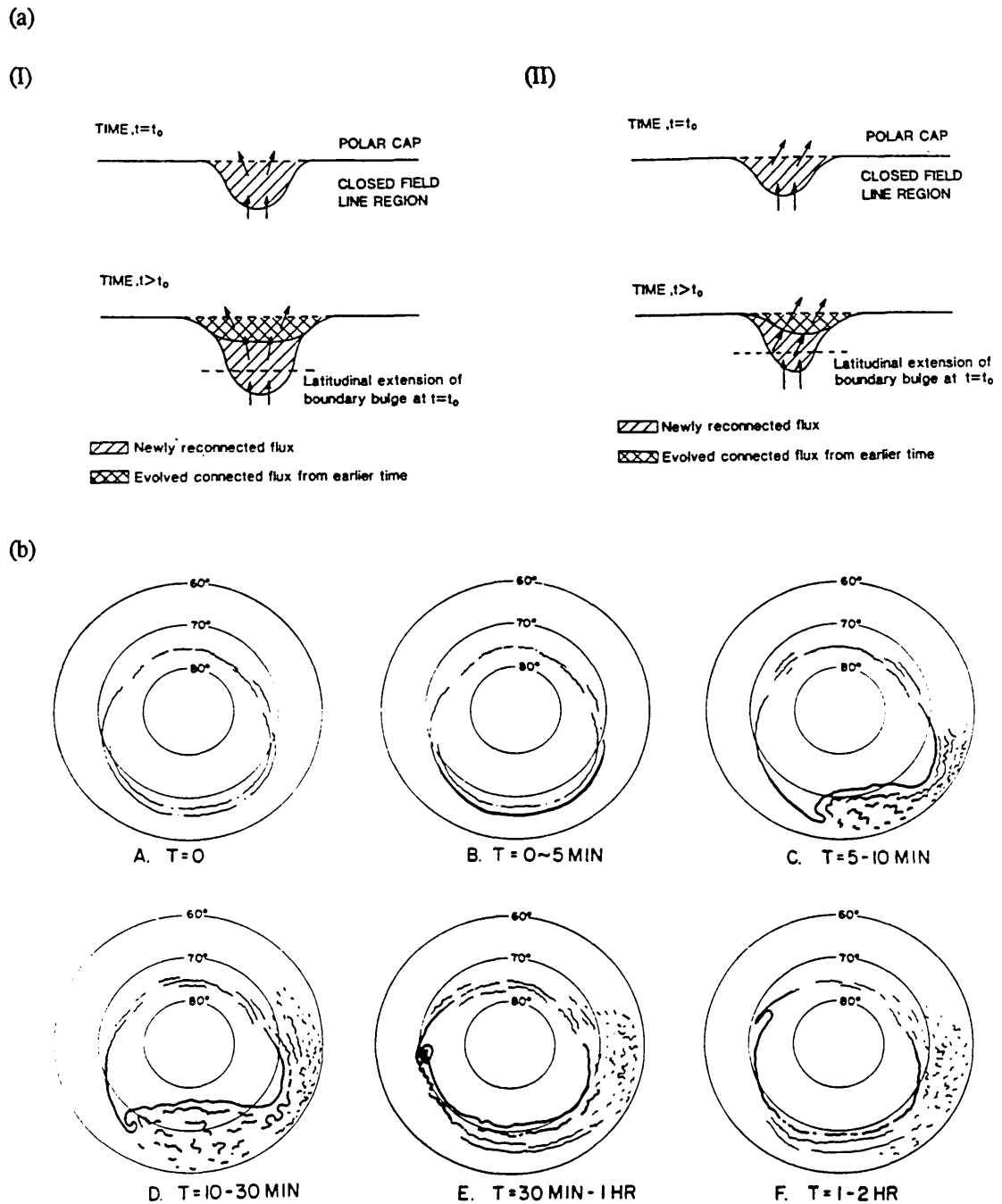


Fig. 2.2. Expected temporal evolution of the ionospheric footprint of newly reconnected magnetic flux, arising from an imbalance between dayside and nightside reconnection rates.

Fig. 2.2a. A dayside polar cap boundary bulge due to localised magnetospheric erosion. The development of the bulge is controlled by the background flow. In case (I) newly opened flux tubes are driven polewards and spread dawn- and dusk-wards within the polar cap, leading to a symmetrical bulge. In case (II) newly opened flux tubes are driven polewards and duskwards, giving rise to an asymmetrical bulge.

Fig. 2.2b. A nightside polar cap boundary bulge due to a rapid burst of reconnection in the magnetic tail during the substorm expansion phase (after Akasofu, 1977). The bulge spreads dawn- and dusk-wards to re-circularise the reduced and distorted polar cap.

2.3. The Ionospheric Flow Model.

The flow in the ionosphere induced on closed field lines by the solar wind is an $\mathbf{E} \times \mathbf{B}$ drift where the electric field, $\mathbf{E}$, is that imposed by the potential condition around the polar cap boundary. The magnetic field at ionospheric levels is changed little by geomagnetic activity and thus one assumes quasi-electrostatic conditions i.e. $\nabla \times \mathbf{E} = 0$. The assumption should be good as long as the flow is well below the Alfvén speed; in the dayside ionosphere it is likely to be of the order 10^6 m s^{-1} . Typical flow speeds observed are less than 1% of the Alfvén speed.

Many workers have developed a range of magnetospheric and ionospheric convection models, using different approximations and varying levels of sophistication. Generally these fall into two classes.

Because of the lack of complete experimental coverage and the theoretical complexity of the system, an empirical approach is often used. Temporal records of geomagnetic parameters at different locations are combined to derive a self-consistent overall potential distribution (e.g. Heppner and Maynard, 1987; Kamide et al., 1981).

Alternatively, simplified theoretical models are developed. These are generally concerned with describing one particular process or observed feature (e.g. Jaggi and Wolf, 1973). Although note that Wolf and his group have developed fairly complex computational models by a process of successively adding different effects (Harel et al., 1981; Wolf et al., 1982).

For our study we chose to adopt the latter approach. As in Wolf's approach, we shall assume that a potential distribution is specified around a curve in the ionosphere, the polar cap boundary. We shall modify the assumption a little by excluding the nightside and imposing a potential variation along the dawn/dusk meridian corresponding to a steady flow of plasma towards the sun as we are only interested in the dayside. We assume that in the closed field line region between the polar cap boundary and some low latitude boundary (the equator in our case) there exist no sources of field-aligned currents. Plasma pressure gradients (Southwood, 1977), [or equivalently particle magnetic drift effects (Jaggi and Wolf, 1973)] may be the source of such currents and can strongly modify the flow pattern at low latitudes. Indeed we present an example of such an effect in Chapter 5. Non-uniform conductivity can also modify the flow in this region by generating field-aligned current.

Our model ionosphere is based on that used in the appendix of Jaggi and Wolf (1973). The ionosphere is taken to be a thin two-dimensional spherical shell permeated by a uniform, locally-vertical magnetic field. The latter means that we cannot expect our model

to be useful at low latitudes. We are only concerned with mid- and high-latitude flows. Further, corotation is also not included, again a low latitude effect.

The distribution of electric field in the shell is determined by the requirement that, in the absence of sources of field-aligned current the horizontal ionospheric current, $\mathbf{J}_I$, has zero divergence.

$$\text{div}(\mathbf{J}_I) = 0 \quad (2.1)$$

Assuming height integrated Pedersen and Hall conductivities, Σ_P and Σ_H , equation (1) becomes

$$\text{div}(\Sigma_P \mathbf{E} + \Sigma_H (\hat{\mathbf{b}} \times \mathbf{E})) = 0 \quad (2.2)$$

For a locally vertical, uniform magnetic field ($\mathbf{B} = B\hat{\mathbf{b}} = -B\hat{\mathbf{r}}$), and writing $\mathbf{E}$ in terms of the electrostatic potential we get

$$\Sigma_P \nabla^2 \Phi + \nabla \Phi \cdot \nabla \Sigma_P + (\nabla \Phi \times \hat{\mathbf{r}}) \cdot \nabla \Sigma_H = 0 \quad (2.3)$$

If the conductivity distribution is uniform, equation (3) reduces to Laplace's equation

$$\nabla^2 \Phi = 0 \quad (2.4)$$

A non-uniform conductivity distribution may be readily incorporated into the model, as can a non-vertical magnetic field, but we do not study such effects here.

Using spherical polars followed by a transformation of elevation angle, λ , equation (2.4) becomes

$$\frac{\partial^2 \Phi}{\partial^2 \phi} + \frac{\partial^2 \Phi}{\partial x^2} = 0 \quad (2.5)$$

where ϕ is the magnetic longitude and x is related to the magnetic colatitude, θ ($= 90^\circ - \lambda$), by

$$x = \ln(\tan(\theta/2)) \quad (2.6)$$

The elliptic equation (2.5) is simple to solve numerically using the method of successive over-relaxation on a uniform (ϕ, x) grid. The solution can then be converted to (ϕ, θ) coordinates for convenience. Lines of equal potential are the ionospheric flow streamlines. The flow velocity vector, $\mathbf{v}$, is simply the $\mathbf{E} \times \mathbf{B}$ drift.

$$\mathbf{v} = \frac{1}{r_E B \sin \theta} \frac{\partial \Phi}{\partial \phi} \hat{\theta} - \frac{1}{r_E B} \frac{\partial \Phi}{\partial \theta} \hat{\phi} \quad (2.7)$$

The high Alfvén speed in the ionosphere implies a time scale of the order 10 s for the communication of any disturbance across the whole dayside. For changes on time scales long compared with this we can solve equation (2.5) varying only boundary conditions and/or boundary position to produce a series of quasi-steady flow patterns consistent with changing conditions in space.

Our model is applied to a bounded area in the ionosphere limited by the polar cap boundary at high latitude and by the magnetic equator or some other low-latitude boundary. Except for one case (section 2.4.2. (iv)), only the dayside convection pattern is considered and then the model area is limited at the dawn and dusk meridians also. This condition can be relaxed so that the model is extended to all magnetic local times, but it is unlikely that the uniform conductivity approximation used here is a good one on the nightside.

At the selected boundaries we must specify the potential, or the normal horizontal electric field, or some linear combination of the potential and field. At the equatorial or low latitude boundary the boundary condition is that no flow is allowed across it and thus we require here a constant (zero) potential. For the dawn and dusk meridians (when applicable) we choose a condition specifying the sunward component to the flow. The condition used in the examples shown here includes some effects of shielding of the convection electric field from low latitudes on the nightside. Our ignoring field-aligned current sources on the dayside means that we are ignoring the effects of dayside ring current shielding. There is a large discrepancy between day and nightside shielding times (Jaggi and Wolf, 1973; Southwood, 1977) and so this is reasonable when considering dynamic effects. Over long time scales the effect of shielding is included by employing an off-equatorial lower boundary on the dayside as well as at night. However, we find that the convection at high latitudes is relatively insensitive to the location of the lower boundary.

Once the boundary conditions have been chosen over the polar cap boundary, the high latitude boundary, the solution for the potential and field in the shell can be found. The effect of both the boundary motion and the boundary shape can be studied by choosing an appropriate high latitude boundary condition. We can both change the position of the boundary and the distribution of potential along it. We start by assuming that the boundary is at about 70° , consistent with the models of Heppner and Maynard (1987) and Heelis (1984) for high K_p .

2.4. Results.

We have limited the computations shown here to conditions producing symmetry about the noon meridian and between the northern and southern hemispheres. There is no reason in principle why these like many of our other assumptions cannot be relaxed. We shall for simplicity describe in detail only the northern hemisphere dusk cell flow pattern. Symmetry allows one to modify the statements made for other sectors.

2.4.1. *Steady state convection.*

We look first at two simple cases of steady, continuous flux transfer. The reconnection rate on the dayside is taken to be equal to that on the nightside. Thus the total amount of open flux is a constant and the polar cap neither expands nor contracts and specifying a reconnection rate simply corresponds to specifying a potential distribution around a fixed polar cap boundary in the ionosphere. On the global scale plasma simply circulates in the classical twin cell manner but the distribution of the flow depends on how the reconnection rate varies in local time along the magnetopause.

2.4.1. (i) *Reconnection across the whole dayside magnetopause.*

In this case, the case in which the potential would be most evenly distributed inside the polar cap itself, the reconnection rate is assumed to be greatest near the noon meridian, and is chosen to fall off in a sinusoidal manner towards the dawn and dusk flanks. The maximum cross-boundary flow is taken to be 1 km s^{-1} , a boundary condition corresponding to a cross polar cap potential of 219 kV. Fig. 2.3a shows the expected flow streamlines (equipotentials) over the dayside for such an event. Fig. 2.3b shows the variation of the flow velocity with latitude at magnetic local times 13:00 MLT, 14:00 MLT, 15:00 MLT and 16:00 MLT. The scales in Fig. 2.3b are based on our choice of 1 km s^{-1} for the value of the peak cross-boundary flow speed (at 12:00 MLT). Variation of this value (and hence the cross-cap potential) varies the scales in Fig. 2.3b proportionately.

The sub auroral flow pattern is characterised by a significant, poleward component to the flow at most local times and latitudes. The flow speed falls off quickly in an approximately exponential manner with co-latitude. As we move away from the centre of the reconnection region at noon MLT flow turns from predominantly poleward to westward at the dusk meridian, reflecting the change in cross-boundary flow. Northward and westward components become comparable at all latitudes near 14:40 MLT for this case. Below 60° magnetic latitude and after 16:00 MLT we observe a small equatorward component to the flow. This is due to the channelling effect of the boundary condition we have imposed on

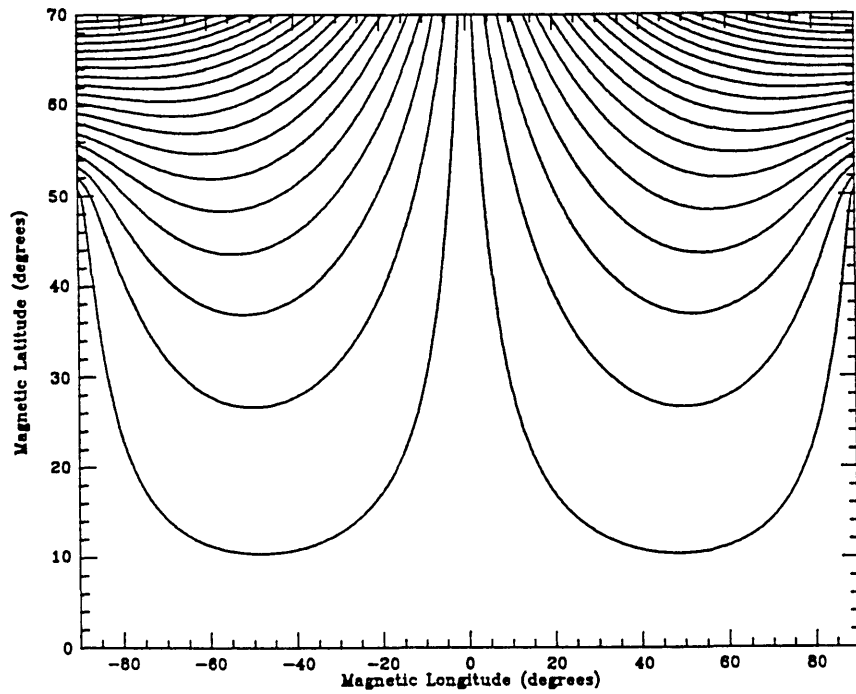


Fig. 2.3a. Expected ionospheric flow streamlines (equipotentials) over the dayside northern hemisphere closed field line region due to steady-state reconnection across the whole dayside magnetopause.

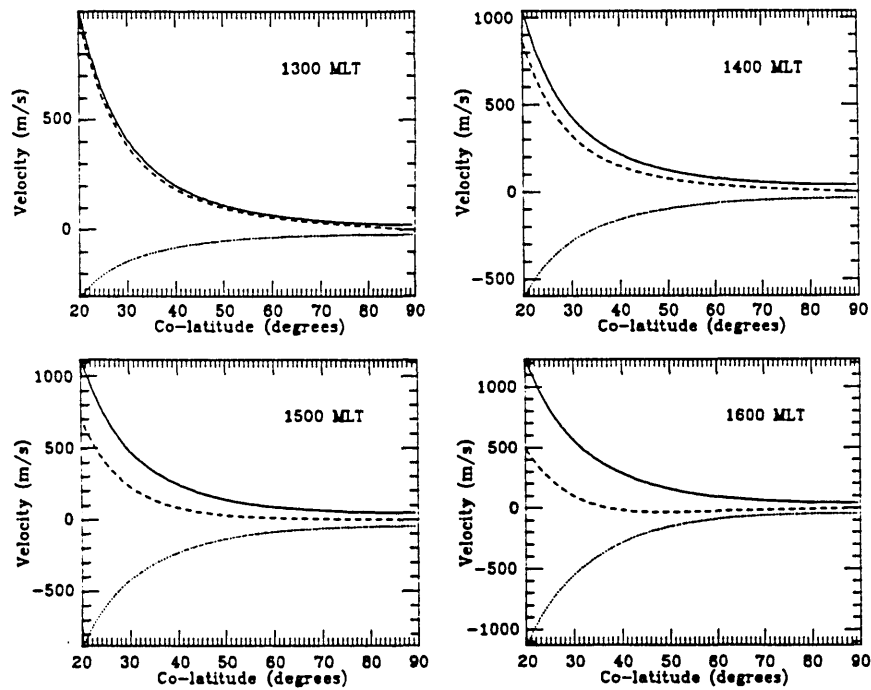


Fig. 2.3b. Resultant variation of flow velocity with latitude at selected magnetic local times - 13:00, 14:00, 15:00, 16:00 MLT.

Solid line - total flow speed. Dashed line - north-south velocity component. Positive corresponds to northward. Dotted line - east-west velocity component. Positive corresponds to eastward.

the terminator. Nightside shielding has confined the flow to higher latitudes at night and there is a divergence to lower latitudes as it emerges onto the dayside.

This pattern is very similar to the steady state results of Heppner and Maynard (1987).

2.4.1. (ii) *Localised reconnection about noon MLT.*

In this case we look at an instance where longitudinally localised reconnection is occurring. Again we assume that the overall amount of open flux remains constant and that the polar cap boundary does not itself move. The dayside cross-boundary flow is taken to be constant and equal to 1 km s^{-1} between 10:00 MLT and 14:00 MLT, and zero elsewhere on the dayside, corresponding to a cross-cap (in this case, cross-throat) potential of 115 kV. Fig. 2.4a shows the resultant flow pattern over the dayside ionosphere. Fig. 2.4b shows the velocity profiles, as in (i). The flow speeds indicated can be rescaled. The values shown are normalised to the nominal cross-boundary flows given above.

The localisation of the reconnection region alters significantly the direction of ionospheric flow over the dayside. We now have predominantly westward flow in the afternoon hours until reconnection draws it polewards near noon. For our case this means that poleward and westward components become comparable for all latitudes at 13:20 MLT (40 minutes within the reconnection region), rather than 14:40 MLT as in case (i). A very small equatorward component exists over much of the late afternoon. Flow speed again decays in an approximately exponential manner with co-latitude.

This pattern is exactly like that proposed by Heelis and Hanson (1976) exhibiting a narrow "throat".

2.4.2. *Non-steady state convection.*

In the next two cases, we address the problem of a flux transfer imbalance between the dayside and nightside ionospheres. When the reconnection rate on the dayside is greater than that on the night we would expect the polar cap to grow. Earlier, we argued that this growth may proceed in two different ways depending on whether the magnetosphere can support a boundary distortion on the time scale of the reconnection.

If the dayside reconnection rate is localised across some longitudinal extent and the concomitant plasma transport is in some way impeded, then we may expect the cap to erode in some non-isotropic manner. The boundary would be distorted equatorwards near the reconnection site creating a bulge in the polar cap. Such a perturbation was illustrated in Fig. 2.2a. In space, the magnetopause is correspondingly moving towards the Earth, or eroding as reconnection takes place.

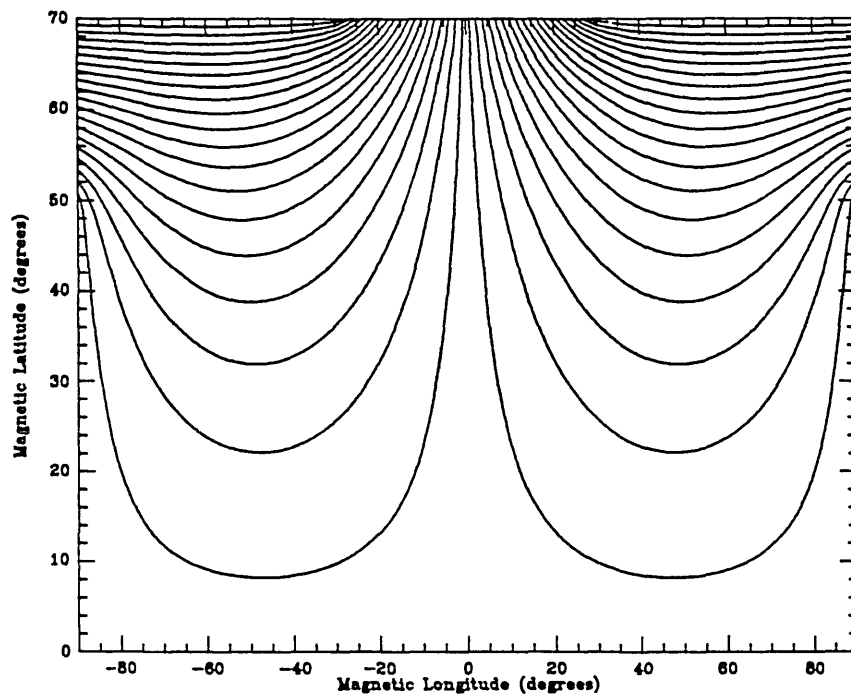


Fig. 2.4a. Expected flow streamlines as in Fig. 2.3a, but due to steady-state localised reconnection at the dayside magnetopause.

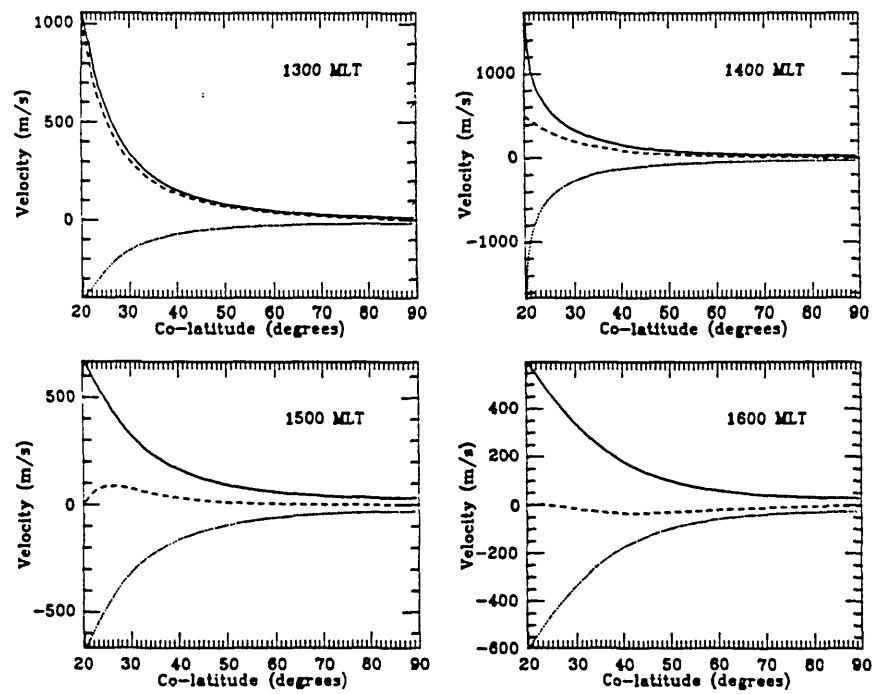


Fig. 2.4b. Flow velocity profiles derived from Fig. 2.4a. See Fig. 2.3b for details.

2.4.2. (iii) *Magnetospheric erosion. Irregular polar cap boundary.*

In this case, we have set a constant reconnection rate between 10:00 MLT and 14:00 MLT, and a cross-boundary flow exactly as in (ii). However we now assume that the dayside reconnection rate has been sufficiently high to have caused erosion and the polar cap boundary has moved equatorwards in the reconnection location. A flow speed of 1 km s^{-1} across a throat now located at 63 degrees magnetic latitude implies a potential in the ionosphere of 152 kV. The precise shape of the bulge will depend on the electromagnetic and mechanical stresses on the newly connected field lines and so will be a function of magnetic local time and interplanetary conditions, principally IMF B_y , as discussed briefly earlier. The edges of the bulge have been shaped to smoothly attach to the regions to east and west where reconnection is not significant. If the bulge has eroded equatorwards to a magnetic latitude of 63 degrees in 45 minutes then the dayside reconnection rate is about $1.9 \times 10^5 \text{ Weber s}^{-1}$ (assuming, in the Earth's frame, a north-south ionospheric flow speed at the throat of 1 km s^{-1} throughout) i.e. in excess of the electrostatic cross-cap potential. Alternatively, a substantial proportion ($\sim 20\%$) of the appended flux could be accounted for by a burst of enhanced ($\sim 200 \text{ kV}$) reconnection over a sufficiently short time scale ($\sim 2 \text{ min}$) that the ionosphere cannot respond directly, as discussed earlier; with a concomitant FTE of comparable size to that argued above for the events observed by Paschmann et al. (1986). Fig. 2.5a shows the instantaneous ionospheric flow pattern, and Fig. 2.5b gives the velocity profiles as before.

The presence of an equatorward bulge corresponding to previous magnetopause erosion has a very important effect on the flow. The flow streamlines can only leave the closed field line region in the localised region near noon where reconnection is occurring and where the boundary is displaced equatorward. Flow has to be diverted equatorward to reach the reconnection region; the flow at all latitudes is directed more equatorward than in the previous cases in order to match the boundary shape. Note also that sunward flow will be fastest near the latitude of the sink and will stagnate in the high latitude pocket created tailward of the boundary bulge. The flow direction will mimic the boundary edge. Such effects can be seen in the velocity profile for 15:00 MLT, just to the duskward side of the bulge. Well duskward of the bulge, the flow reverts to a form very similar to case (ii). The speed falls off in an approximately exponential manner with co-latitude and is predominantly westward, but the equatorward component to the flow is still greater than that in case (ii).

Within the local time zone where reconnection is taking place the flow is very similar to case (ii) with poleward and westward flow components comparable at all latitudes near 13:20 MLT.

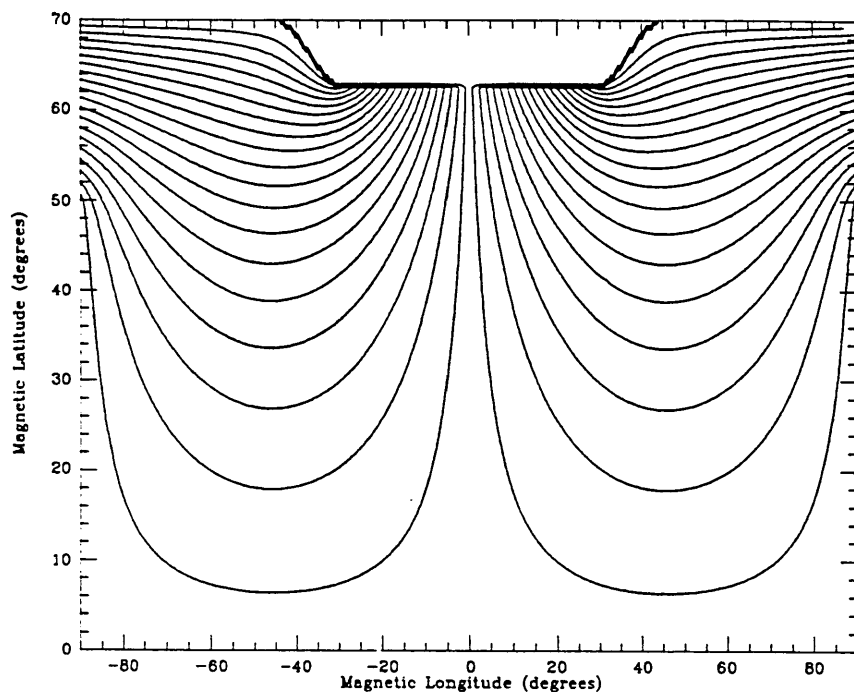


Fig. 2.5a. Expected flow streamlines arising from localised erosion at the dayside magnetopause.

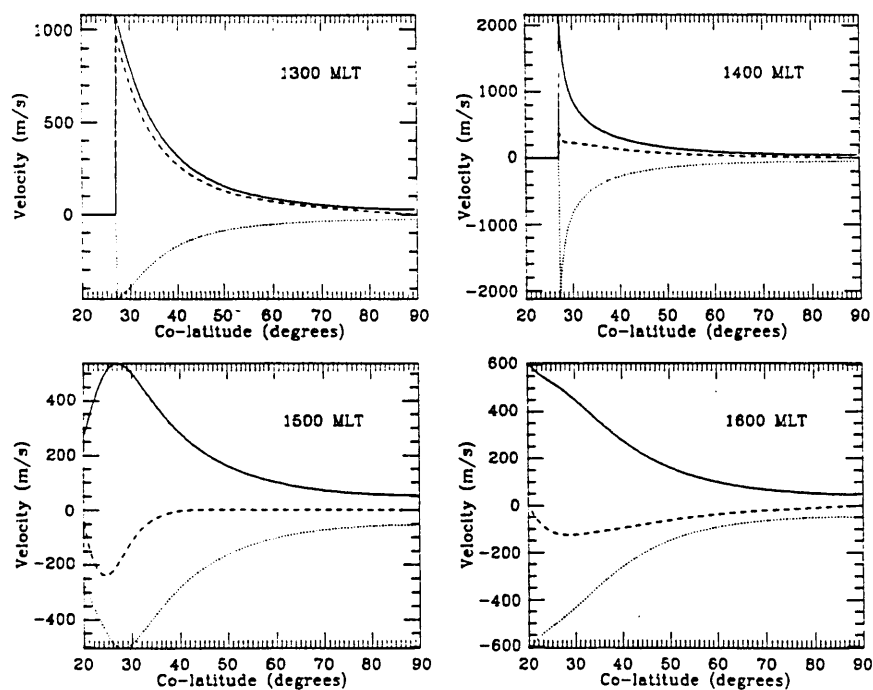


Fig. 2.5b. Flow velocity profiles derived from Fig. 2.5a. See Fig. 2.3b for details.

Flux return event. Collapse of boundary bulge.

This case represents the inevitable restitution of the polar cap boundary after a bout of localised magnetopause erosion. We call the effect the flux return event.

Localised dayside erosion cannot continue indefinitely. Open flux accumulates in the geomagnetic tail and eventually, as stress builds up on the open field lines stretched by the solar wind, the open flux must move bodily tailwards over the polar cap and the locally eroded polar cap boundary would then move back poleward. The motion may be gradual or rapid, probably depending on the temporal nature of a reduction in the dayside reconnection rate in relation to the preceding stress build up. Alternatively, the system may reach a catastrophic limit and trigger a rapid return of flux from the night to the dayside as appears to happen in a magnetic substorm (McPherron et al., 1973), with a consequent release of magnetic stress on open field lines. We shall call the rapid restitution of the locally eroded polar cap boundary to a more circular polar cap a "flux return event" and investigate it further here. We derive the flow pattern in this case by taking the boundary perturbation in the erosion example above and imposing a boundary motion to return the boundary towards its unperturbed position. Fig. 2.6a shows the flow pattern arising from this event. Fig. 2.6b gives the velocity profiles at the key locations used previously.

It is immediately apparent from our results that there is a wholesale reorientation of the flow associated with a flux return event, particularly within a few hours duskward of the bulge. Fig. 2.6 shows that in this mid-afternoon region there exists a vortical flow pattern with rotation in a clockwise sense. In this way there are significant anti-sunward flows within the closed field line region at high latitudes (see Fig. 2.6b, 15:00 MLT). If there exists a continuing background flow from the nightside then at some point sunward and anti-sunward flow will meet. This can be seen at 16:30 MLT for our model and gives rise to weak, largely equatorward flow at high latitudes (see Fig. 2.6b, 16:00 MLT).

Within the longitudinal extent of the eroded region the ionospheric flow pattern remains very similar to that in the two previous cases. Poleward and sunward components are equal at all latitudes near 13:20 MLT as before. This is because there is still a strong poleward motion at the boundary over a localised region about noon MLT.

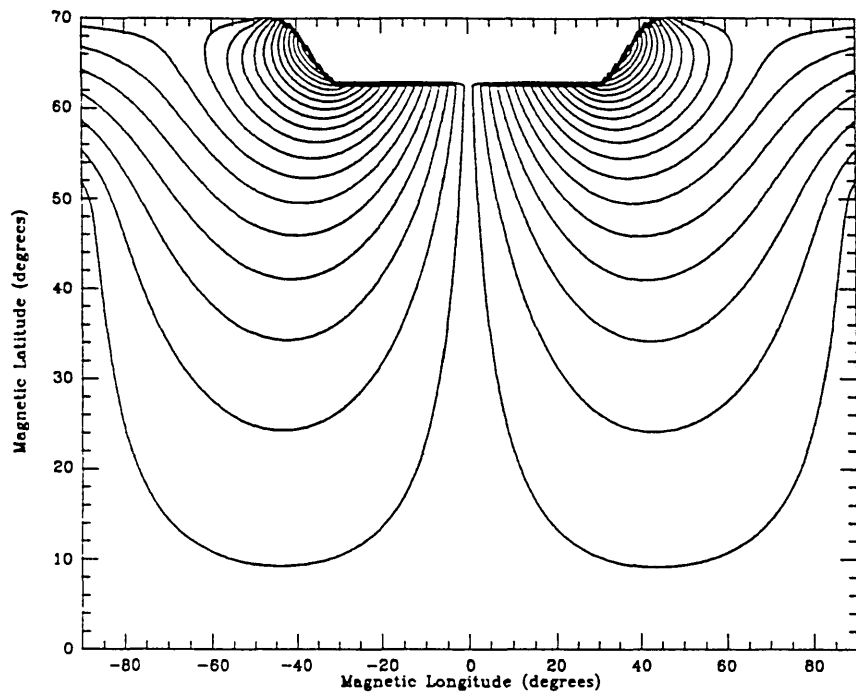


Fig. 2.6a. Expected flow streamlines due to a "flux return event". The polar cap bulge relaxes back to a more circular shape.

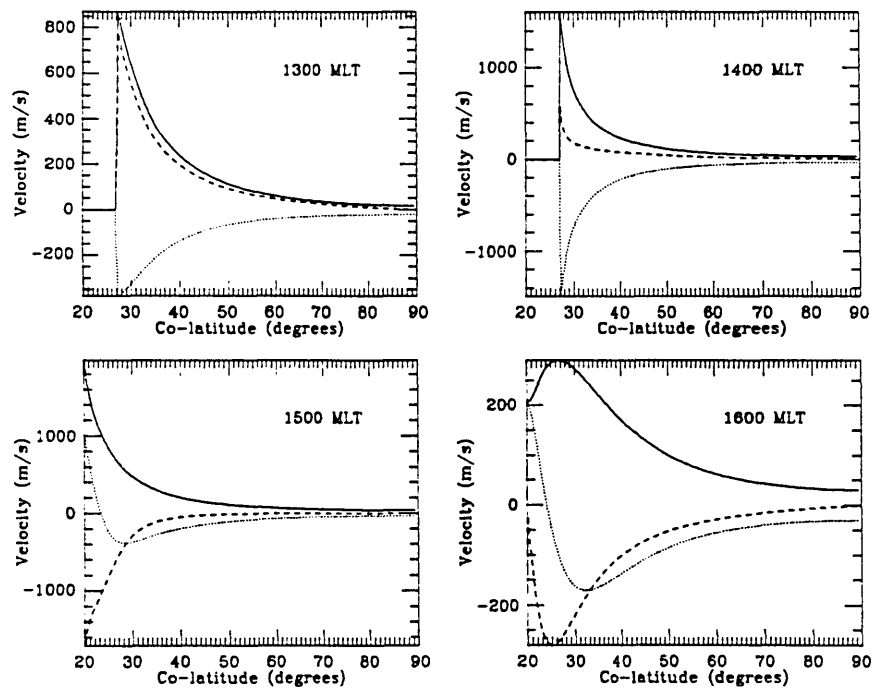


Fig. 2.6b. Flow velocity profiles derived from Fig. 2.6a. See Fig. 2.3b for details.

2.4.2 (iv) *Magnetospheric erosion. Uniform polar cap boundary.*

If the dayside magnetosphere cannot support any significant stress then magnetic pressure gradients arising from erosion will be rapidly dispersed across the polar cap such that it grows uniformly at all local times. The re-distribution of magnetic field lines to isotropise the magnetic pressure generates a circulation of plasma within the magnetosphere and ionosphere. The ionospheric flow pattern associated with the strict maintenance of a circular polar cap boundary was discussed earlier, following the results of Siscoe and Huang (1985). Here, we repeat their analysis for completeness.

In this case we assume that longitudinally localised reconnection is occurring at the dayside magnetopause in the absence of any balancing nightside reconnection such that the polar cap flux increases. Once again, we set the dayside cross-boundary flow to be constant and equal to 1 km s^{-1} between 10:00 MLT and 14:00 MLT, with the boundary initially at 70° latitude. In addition, we assert that the boundary has an equatorward velocity equivalent to the rate of polar cap expansion due to the day-night reconnection rate imbalance. This means that the potential distribution around the polar cap boundary is a summation of an applied cross-throat potential of 115 kV which increases linearly with longitude across the throat, and a potential of 115 kV which decreases linearly with longitude around the entire polar cap boundary to ensure a uniform equatorward polar cap expansion appropriate to the rate of increase of open magnetic flux. This contrasts with case (ii) where the potential was constant along the dayside polar cap boundary away from the throat and it was assumed that reconnection in the tail drained open flux from the polar cap in a restricted local time sector on the nightside to give no net open magnetic flux increase. The model in this example has been extended over an entire 24 hours of local time and plasma is constrained to flow above 40° magnetic latitude, though the results are not very sensitive to this restriction. Fig. 2.7a shows the resultant flow pattern and Fig. 2.7b shows the velocity profiles at the key local times used in the previous examples.

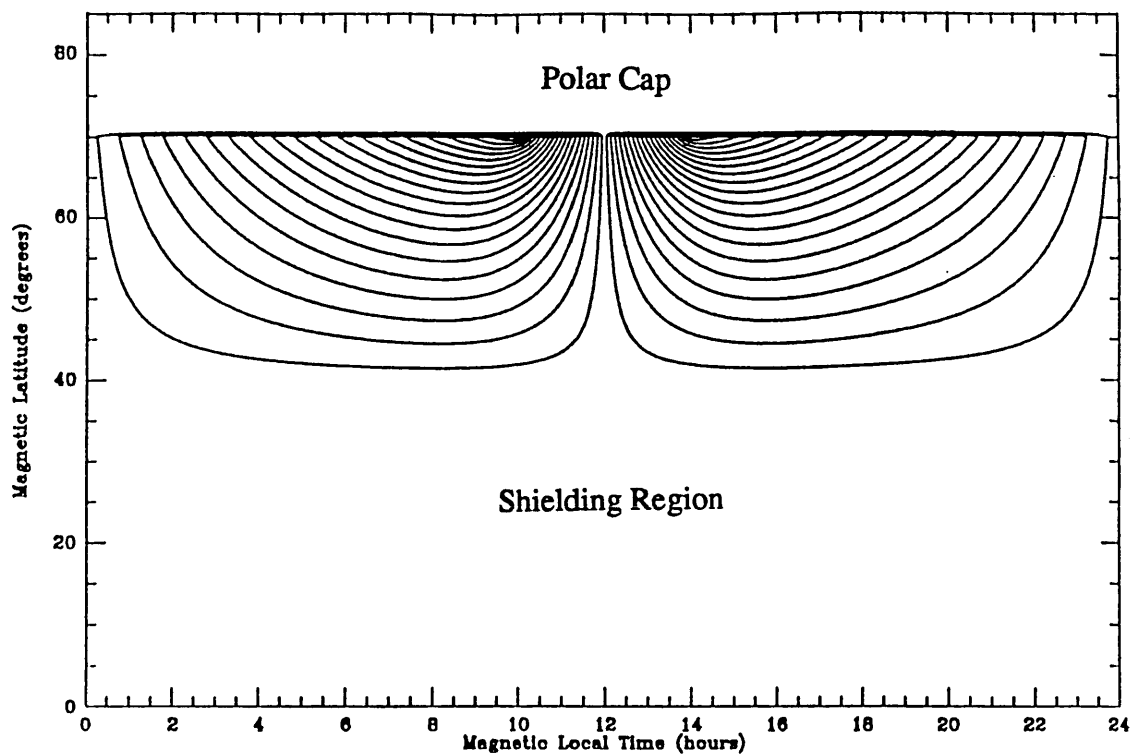


Fig. 2.7a. Expected flow streamlines over the entire northern hemisphere closed field line region due to a uniform polar cap expansion arising from magnetospheric erosion.

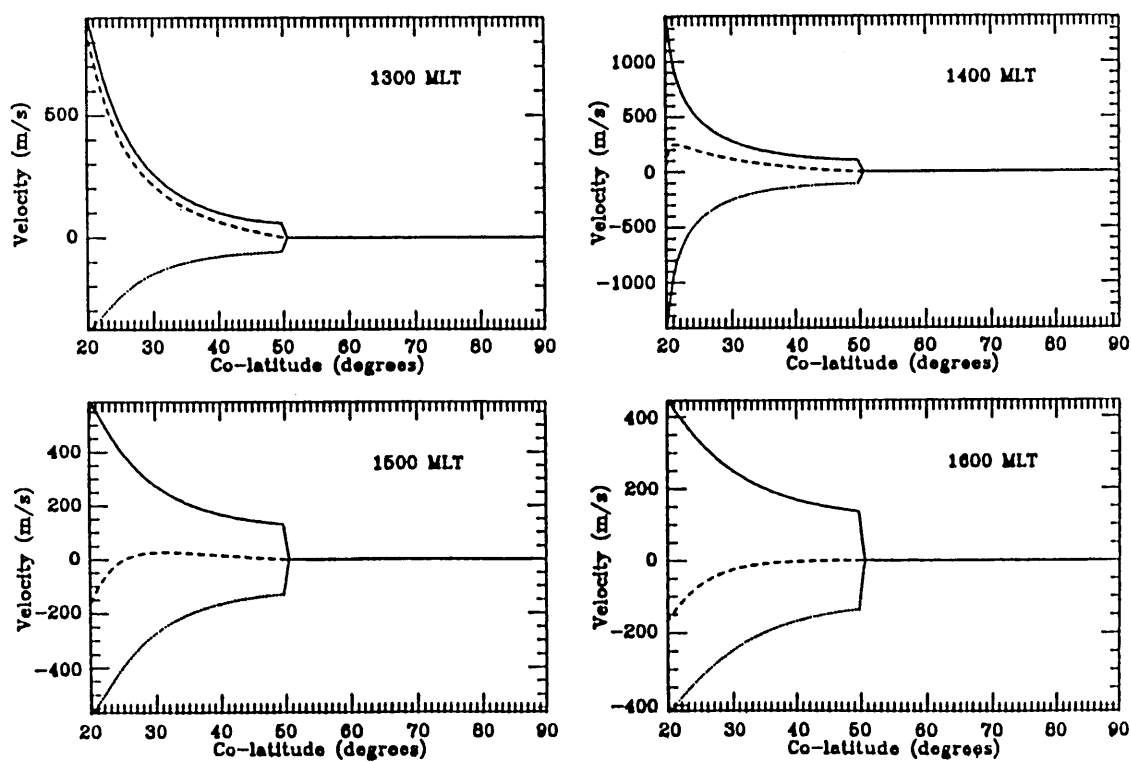


Fig. 2.7b. Flow velocity profiles derived from Fig. 2.7a. See Fig. 2.3b for details.

2.5. Discussion of Model Results.

We have outlined above the effect on dayside ionospheric flow on mid-latitude field lines of five different types of boundary condition. In addition to the concept of uniform polar cap expansion considered by Siscoe and Huang (1985), we have introduced two new terms, the "flux erosion event" and the "flux return event". They are illustrated in section (iii). In the former case the polar cap grows by the localised addition of flux on the dayside, distorting the polar cap from a circular configuration. The latter case represents the ionospheric transient associated with the return of the distorted polar cap to a circular shape.

The flow patterns associated with the five different boundary conditions can mimic the boundary shape or reflect its motion, show equatorward motions in local time zones where reconnection is not occurring, and poleward motion otherwise. Generally, the east-west component of the flow is towards the Sun, or the region where the dayside reconnection rate maximises. However, in the case of the flux return event, ongoing reconnection is not the dominant process controlling the flow. For this event to occur the system must have been primed by a period of sustained erosion. In flux return events tailward flow can be induced on closed field lines and it follows that identification of tailward flow as necessarily a signature of the polar cap proper may at times be questionable. Also strong poleward flows do not necessarily indicate the local time zone where reconnection is occurring. When dayside reconnection is ongoing, poleward flows can be observed outside the longitudinal extent of the neutral line (see 15:00 MLT flow profile, Fig. 2.4b). At other times dayside reconnection may have ceased but poleward flows still exist near noon MLT. This is a feature of the Siscoe and Huang model during dominant nightside reconnection (see Fig. 2.1b). Also, although dayside magnetopause reconnection is a necessary precursor of a flux return event, there may be no reconnection actually occurring during a given event but there will be regions of local time where strong poleward flows are found.

Our calculations are valid on time scales for which the electric field is quasi-static. The Alfvén travel time for a signal to move horizontally throughout the ionosphere is some 10's of seconds. Hence on time scales longer than minutes our models can represent the instantaneous global flow pattern. If conditions at the boundary are changing on a scale of minutes, the ionospheric flow system evolves through a series of appropriate quasi-steady flow patterns in response.

The time scale on which any pattern may be established is not determined by any physical process we have introduced into the model here. A bulge on the boundary (case (iii)) may develop slowly or suddenly (relative to the system Alfvén travel time). In Southwood's (1987) model, a magnetopause flux transfer event creates a small polar cap boundary bulge instantaneously (i.e. in minutes). A period of sustained magnetopause

erosion like that observed by Paschmann et al. (1986), if at all localised in longitude, could give rise to the steady development of a polar cap boundary distortion in the ionosphere if there is some impedance to the large scale plasma flows. Otherwise there is a steady growth of an approximately circular polar cap.

Similarly, the onset of a flux return event or a more isotropic dayside polar cap contraction may be sudden or gradual. Substorms on the nightside of the Earth are associated with a large reconfiguration of the magnetotail field (McPherron et al., 1973) and could be the likely cause of release of stress on polar cap flux tubes attaching to the dayside. Substorm expansion takes place on a time scale of minutes (Akasofu, 1977) and thus the cessation of the polar cap expansion, localised or otherwise, might be more rapid than its initiation.

2.6. Observations.

Our particular motive for the study of dayside ionospheric flow patterns during geomagnetic activity stems from observations made by the SABRE (Sweden And Britain auroral Radar Experiment) radar. This instrument is a bistatic facility which uses a naturally occurring plasma instability to deduce electron drift velocity fields in the E region ionosphere (Nielsen et al., 1983; Waldock et al., 1985) and its operation is discussed in detail in Chapter 5. Fig. 2.8 shows the location of the SABRE field of view in relation to the magnetic L shells. To deduce the velocity field in the geomagnetic coordinate system it is necessary to rotate clockwise from the local geographic frame.

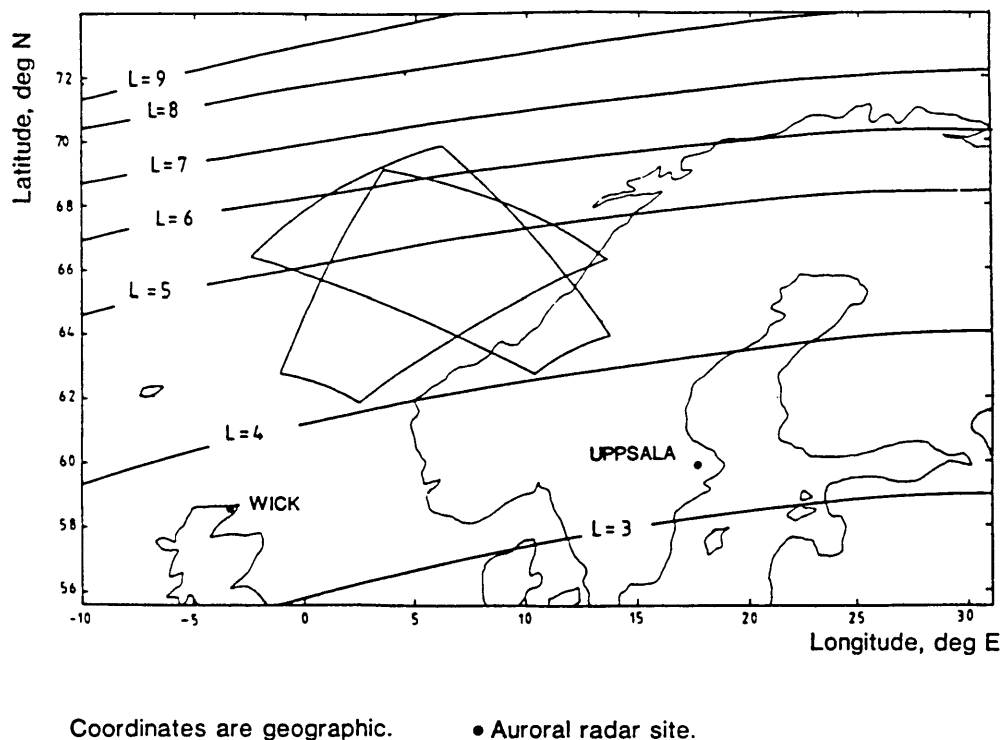


Fig. 2.8. The viewing areas of the SABRE radars in relation to the magnetic L shells.

In Fig. 2.9 we show a comparison of the ionospheric flow data recorded at 14:30 UT on September 4, 1984 (Day 248) with the latitudinal profiles of the auroral zone flow predicted from the uniform polar cap expansion model, case (iv) above. The data comes from a period we have studied using simultaneous spacecraft, ground magnetometer and other geophysical data (see Chapter 4). The day is of great inherent interest as the day on which the IRM spacecraft detected reconnection and sustained magnetopause erosion for of order 30 minutes (Paschmann et al., 1986).

Flow velocity components are inferred from a latitudinal chain of ground magnetometers in Scandinavia under the assumption that ground conductivity effects can be neglected and that the horizontal ground magnetic perturbation is due to a uniform overhead current sheet (see Chapter 4) (Fig. 2.9b). A radar estimation of the $\mathbf{E} \times \mathbf{B}$ drift velocity is made from a central latitudinal slice of the SABRE viewing area corresponding to four latitudinal bins: $64\text{--}65^\circ$, $65\text{--}66^\circ$, $66\text{--}67^\circ$, $67\text{--}68^\circ$ geographic latitude, and averaged over $5\text{--}7^\circ\text{E}$ geographic longitude (Fig. 2.9a). The velocity is given in m s^{-1} , with the north-south and east-west components, and total speed shown. Positive values correspond to northward and eastward components, where the northward direction is $\sim 20^\circ$ anti-clockwise of the local geographic North (see later discussion). To normalise the measurements to the model predictions we have reduced the measured flow components by a factor of two.

Firstly, we examine the observed and modelled east-west flow components. The SABRE observations at 16:00 MLT agree quite well with the modelled east-west flow component in that they reproduce the expected poleward flow gradient. However, the magnetometer data from 17:00 MLT and covering a wider latitudinal range than SABRE shows a departure from the modelled latitudinal profile. Below $\sim 64^\circ$ latitude the poleward gradient to the east-west flow component seen in the model is also evident in the data, but poleward of this latitude the observed westward flow decreases, whilst the model predicts an increase. The equatorward gradient to the flow at the poleward edge of the auroral zone observed here is a common feature of the ionospheric convection (Etemadi et al., 1988). The effect may be attributable to two factors. Firstly, though reconnection is the dominant mechanism driving the magnetospheric convection, viscous processes may also occur concurrently. The effect of this co-existence upon the magnetospheric circulation is to impose a viscous drag on the sunward convecting closed field lines, particularly near to the dawn/dusk flanks (Cowley, 1982). In the ionosphere this has the result of retarding the plasma flow at the poleward edge of the auroral zone and may thus give rise to the observed equatorward flow gradient in this region. Secondly, particle precipitation in the outer magnetosphere can relatively enhance the ionospheric Pedersen and Hall conductivities in the auroral zone. The ionospheric convection is likely to avoid regions of high Pedersen conductivity because more energy would need to be expended to sustain the $\mathbf{E} \times \mathbf{B}$

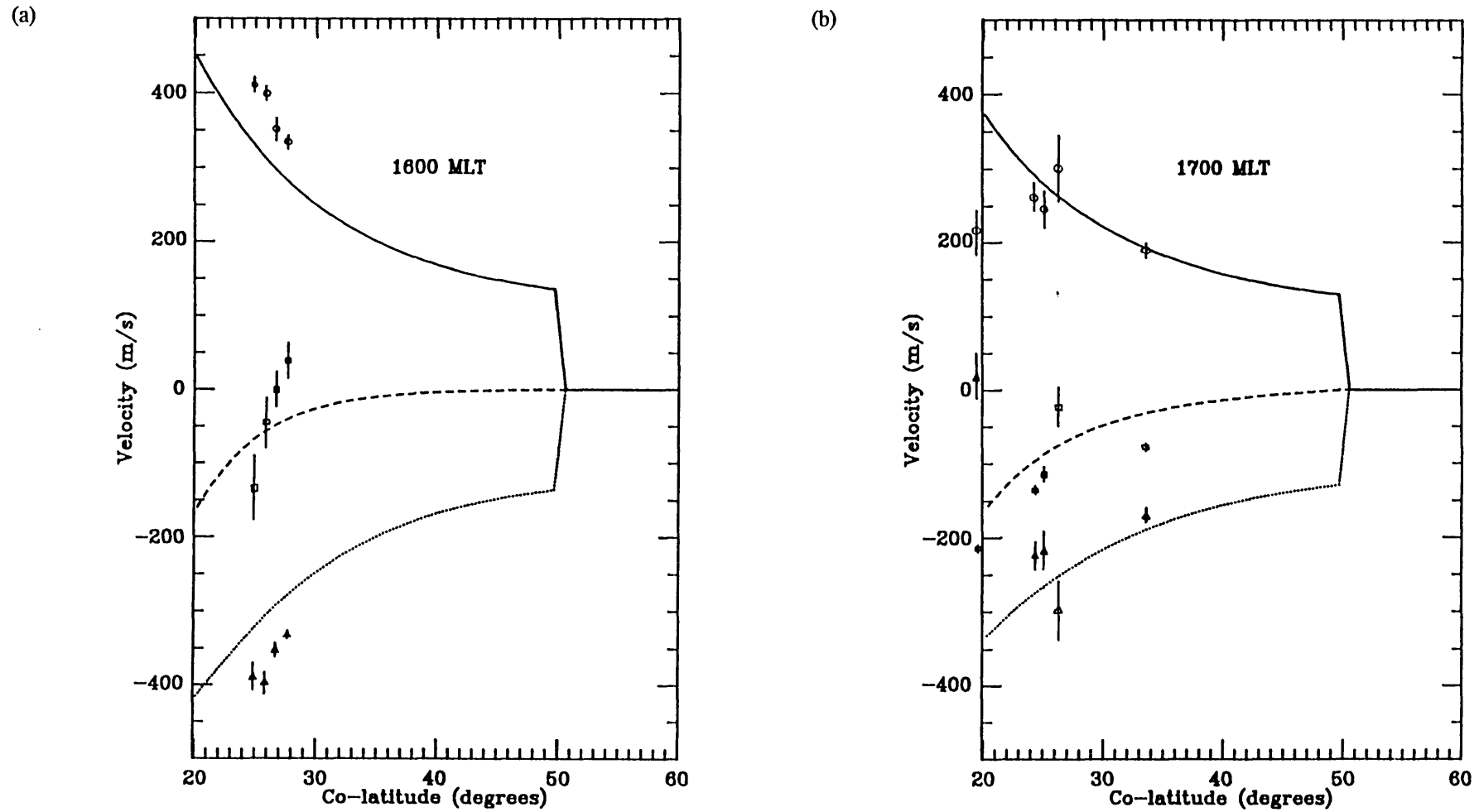


Fig. 2.9. A comparison of measured ionospheric flow velocity components with those derived from the uniform polar cap expansion flow model (see Fig. 2.7). Measurements were made at 14:30 UT on September 4, 1984, using the SABRE radar (Fig. 2.9a) and a Scandinavian magnetometer chain (Fig. 2.9b). Circles - total flow speed. Squares - north-south velocity component. Triangles - east-west velocity component.

motion. Hence, if the particle precipitation into the F region ionosphere generally peaks at the poleward edge of the auroral zone then this effect may also help to explain the equatorward flow gradient in this region. The flow model developed above can be readily extended to allow for ionospheric conductivity gradients. Results (not shown) indicate that an equatorward flow gradient near to the polar cap boundary can exist for sufficiently large poleward conductivity gradients.

Secondly, comparison of the model with the observed equatorward flow speeds is found to be particularly instructive in understanding the prevailing magnetospheric conditions. Whereas the steady state flow model (case (ii) above) would predict a purely westward component to the flow at the local time of observation (see 16:00 MLT, Fig. 2.4b) the model used here, invoking an expansion of the polar cap, successfully accounts for the observed equatorward flow component. The inferred polar cap expansion from the essentially instantaneous measurements is supported by the subsequent observations, in addition to the in-situ observation of erosion at the magnetopause mentioned above. A more complete analysis of the available data is contained in Chapter 4.

In the data presented above we employed a transformation from the geographic spherical polar coordinate frame in which the data were measured to the spherical polar coordinate frame in which the model was calculated, which is orientated not by the geographic pole but by the polar cap centre. The choice of coordinate frame is important in interpreting data and so at this stage we consider the coordinate transformations.

In general, we would expect the location of the polar cap centre to be determined by the terrestrial magnetic field and thus a first approximation of the polar cap centre position might be at the magnetic pole as calculated by a spherical harmonic expansion of the Earth's measured magnetic field (Gustafsson, 1984). For the epoch 1980 the northern magnetic pole was located at (78.8 °N, -70.76 °E). Thus to find the location in polar cap coordinates of a ground station whose position is known in geographic coordinates we employ a rotational transformation:

$$\mathbf{r}_c = \mathbf{M} \mathbf{r}_g \quad (2.8)$$

where $\mathbf{M}$ is the transformation matrix to rotate the Cartesian geographic position vector, $\mathbf{r}_g$, to the Cartesian polar cap centred position vector, $\mathbf{r}_c$. $\mathbf{M}$ is given by:

$$\mathbf{M} = \begin{pmatrix} \cos\alpha \cos\beta & \cos\alpha \sin\beta & -\sin\alpha \\ -\sin\beta & \cos\beta & 0 \\ \sin\alpha \cos\beta & \sin\alpha \sin\beta & \cos\alpha \end{pmatrix} \quad (2.9)$$

where $(90^\circ - \alpha, \beta)$ are the geographic polar coordinates of the polar cap centre (the geomagnetic pole). Expressing the Cartesian position vector in polar coordinates we have the relations:

$$\tan\phi_c = \frac{M_{22}.\sin\theta_g.\sin\phi_g + M_{12}.\sin\theta_g.\cos\phi_g}{M_{21}.\sin\theta_g.\sin\phi_g + M_{11}.\sin\theta_g.\cos\phi_g + M_{31}.\cos\theta_g} \quad (2.10)$$

$$\cos\theta_c = M_{23}.\sin\theta_g.\sin\phi_g + M_{13}.\sin\theta_g.\cos\phi_g + M_{33}.\cos\theta_g \quad (2.11)$$

where θ is the angular displacement from the appropriate dipole axis and ϕ is the azimuthal angle in the plane perpendicular to the appropriate dipole axis. $\phi_c = 0^\circ$ defines the plane containing the polar cap centre and the geographic pole. Using the above relationships we can calculate the locus in the polar cap frame of a given latitude circle and determine the angle, γ , between the local tangents to a latitude circle in the two frames. This angle varies with geographical position due to the offset of the polar cap centre from the geographic pole. However, since the magnetic pole is fixed with respect to the rotating Earth and hence with respect to the geographic pole the angle, γ , is invariant with time at a given observing station in this example; the station always remains in a fixed position with respect to a polar cap centred on the geomagnetic pole. It is found that the observations made in the geographic frame near to the centre of the SABRE field of view ($66.5^\circ\text{N}, 5.0^\circ\text{E}$) should be rotated clockwise by 28.5 degrees to transform them into the local polar cap centred frame.

An additional complication to the transformation of the flow measured in the geographic frame to that in the polar cap centred frame is that the effect of dayside reconnection is to drive the ionospheric plasma in a generally anti-solar direction. This flow direction is then fixed with respect to the Sun-Earth frame, but not in the rotating Earth frame. In order to determine the location of an observing station with respect to the externally-imposed non-rotating ionospheric flow pattern we must transform the polar cap centred longitude, ϕ_c , of the observing station determined in the rotating Earth frame to that in the stationary Sun-Earth frame. Thus the new longitude, $\phi(t)$, determining the station's location with respect to the ionospheric flow pattern i.e. its magnetic local time, is $\phi_c + \delta$, where $\delta(t)$ is the angle between the meridian $\phi_c = 0^\circ$ and the Sun-Earth line. Hence when the $\phi_c = 0^\circ$ meridian is aligned with the Sun-Earth line i.e. 12 LT or 24 LT at the polar cap centre, then $\delta(t) = 0^\circ$. When the $\phi_c = 0^\circ$ meridian lies at the dawn or dusk solar terminator then $\delta = -90^\circ$ or $\delta = 90^\circ$, respectively. In the approximation of the polar cap centre being at the geomagnetic pole and observations at equinox we find $\delta(t) = (\text{UT} - 12) * 15^\circ + \beta$. Near to the centre of the SABRE field of view ($\phi_c + \beta$), essentially the difference between MLT and UT, is calculated to be 2.1 hours. Additionally, the geomagnetic latitude is found to be 0.2 degrees higher than the geographic latitude.

Fig. 2.10 shows the statistical auroral zone ionospheric flow pattern in geographic coordinates derived by Waldock et al. (1985). The observation of the stagnation region between the morning (eastward) flow cell and the afternoon (westward) flow cell at $(09:00 \pm 00:30)$ UT implies the flow reversal to be at $(11:05 \pm 00:30)$ MLT. It can be seen that a systematic clockwise rotation of the flow vectors by $\sim 30^\circ$ would yield a more symmetrical flow pattern with predominantly zonal flow near to the dawn/dusk meridian, in better agreement with the model dayside flow pattern e.g. compare the strongly geographically poleward flows at 8 UT, ~ 1 hour prior to the east-west convection reversal and flow stagnation region, with the geographically zonal flows at 10 UT, ~ 1 hour after the reversal. (N. B. in this figure the geomagnetic latitude scale is 2.1 degrees lower than geographic latitude).

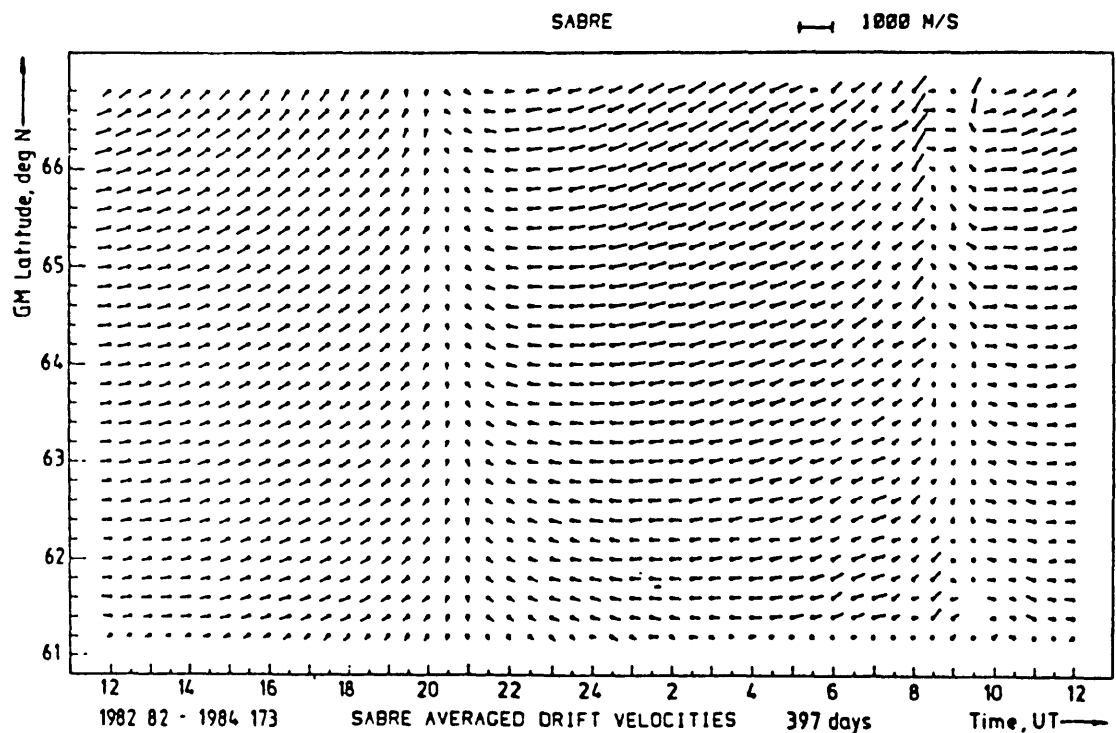


Fig. 2.10. The diurnal convection pattern measured by SABRE, averaged over all magnetic conditions between Day 82, 1982 and Day 173, 1984 (from Waldock et al., 1985).

In Fig. 2.11 we present the expected diurnal variation of the geographic northward and eastward flow components at a location close to the centre of the SABRE field of view using a twin cell flow model like that shown in case (ii) above and assuming the polar cap centre to be co-located with respect to the geomagnetic pole. In addition, we show measured flow data from the SABRE radar during two of the rare occasions when backscatter was continuous over almost a whole day. Comparison of the data is good over long

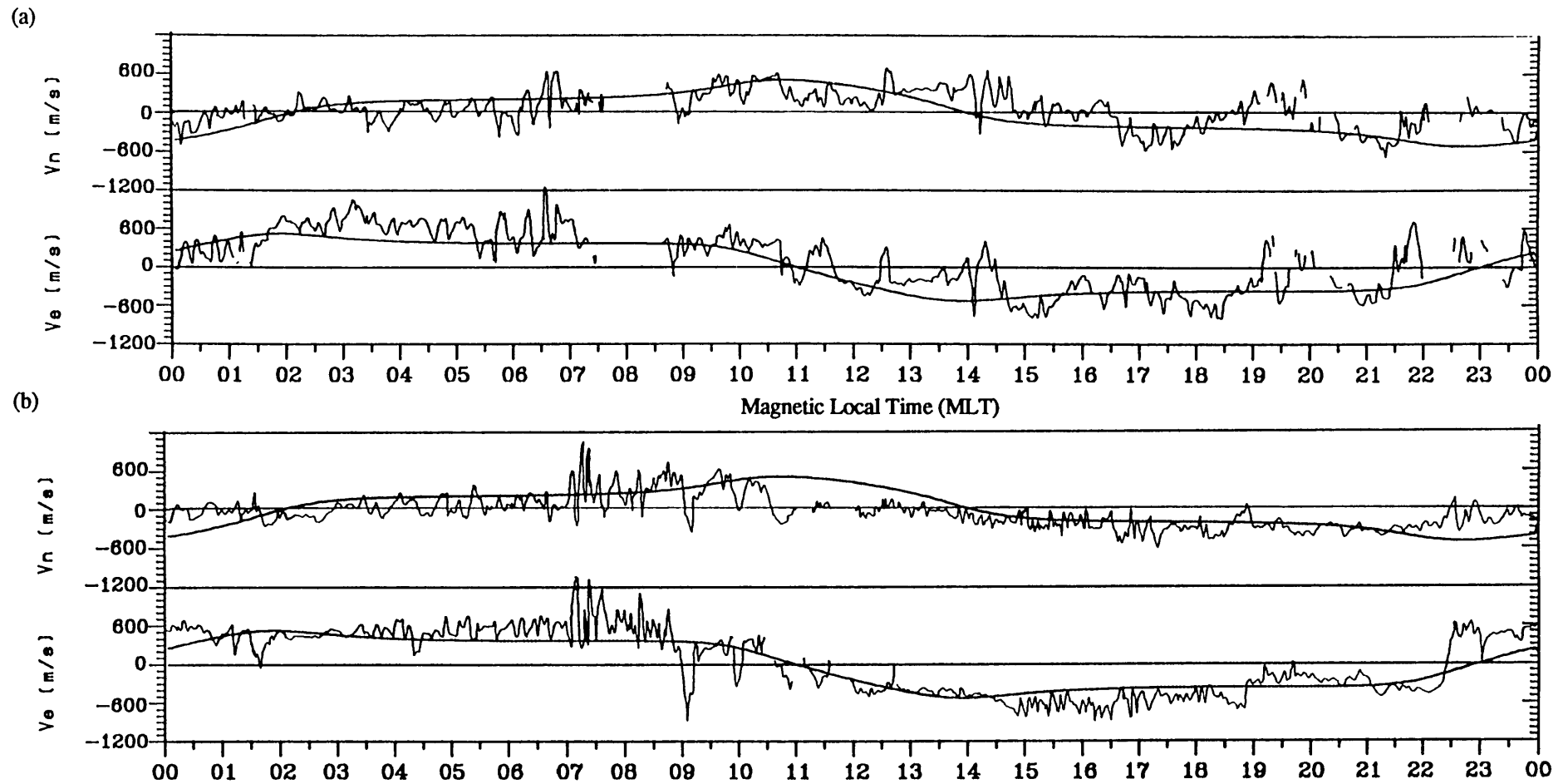


Fig. 2.11. Comparison of the diurnal convection pattern measured by the SABRE radar during two storm days (Day 249, 1982, Fig. 2.11a; Day 63, 1983, Fig. 2.11b) with the diurnal flow variation expected at this site due to the ionospheric convection pattern shown in Fig. 2.4. See text for details.

(~ hours) time scales suggesting that the steady state twin-cell flow pattern with a limited reconnection "throat" is a good approximation of time-averaged ionospheric convection. We note that the effect of measuring in the geographic frame has the effect of displacing the east-west dayside flow reversal one hour of MLT earlier to 11:00 MLT such that the observation of the flow reversal by SABRE at ~ 09:00 UT in these events and in the statistical study of Waldock et al. discussed above in fact implies a dayside flow reversal in the polar cap frame at ~ 12:00 MLT i.e. at the ionospheric projection of the subsolar magnetopause. Whilst the low frequency component of the measured ionospheric flow can be well modelled in these cases, for short intervals, however, the flow may deviate significantly from the steady state predictions. The time-dependent nature of the ionospheric circulation apparent from this comparison will be a central focus for this thesis.

Another departure from the large scale ionospheric flow approximation developed above may arise from our assumption that the polar cap centre is co-located with the geomagnetic pole. Observations from polar orbiting spacecraft indicate that the centre of the auroral oval is at times displaced from the geomagnetic pole, generally towards the nightside (Chubb and Hicks, 1970; Meng et al., 1977). This has been supported by radar observations from the ground showing that a ground station, rather than remaining at a fixed position relative to the polar cap as argued above, is closer to the polar cap at night than during the day (e.g. Todd et al., 1988). The effect of an anti-sunward displacement of the polar cap centre from the geomagnetic pole has the effect of causing the polar cap centre to rotate with time about the geomagnetic pole in a coordinate system fixed with respect to the rotating Earth.

As an example of the modification to our initial assumptions this effect can produce we return to the data presented earlier from the event on September 4, 1984 and to be discussed in more detail later in Chapter 4. Polar orbiting spacecraft observations reveal at ~12:20 UT a difference of ~ 8 degrees in the latitude of the poleward edges of the auroral oval at ~ 11:00 MLT and ~ 21:00 MLT. The observations are inconsistent with a circular polar cap centred on the geomagnetic pole, but can be fitted to a circle offset ~ 5 degrees anti-sunward of the geomagnetic pole, in agreement with the average anti-sunward displacement determined by Meng et al. (1977). Assuming this displacement to prevail at the time of the observations studied (14:30 UT), we find that the angle between the local tangents to the geographic and polar cap centred latitude circles at the Scandinavian magnetometers and in the SABRE field of view is ~ 20°. Additionally, we find that the polar cap centred latitude is ~ 2° lower than geographic latitude in the SABRE field of view, and the MLT is ~ 1.4 h later than UT, whereas, in the Scandinavian local time sector, the polar cap centred latitude is ~ 4° lower than geographic latitude, and the MLT is ~ 2.4 h

later than UT. The data presented in Fig. 2.9 used this estimate of the geographic - polar cap coordinate transformation.

The location of, for example, the east-west flow reversal indicative of the polar cap boundary can thus be systematically altered by measurement in an inappropriate coordinate frame. Additionally, it is apparent that in order to understand how disparate ground based observations of the ionospheric convection and allied phenomena conjoin it is important to order the observations into an appropriate coordinate system. We consider this further when we present evidence for an isotropic expansion of the polar cap in Chapter 4.

2.7. Conclusions.

We have investigated some simple models of the response of the mid-latitude part of the global ionospheric plasma flow system to changes in the conditions imposed at high latitudes by the solar wind-magnetospheric interaction during disturbed times. The context throughout has been that of the open magnetosphere (Dungey, 1961). In particular, we have discussed the effects of enhanced reconnection in a local time sector near noon and the effect of imbalances between dayside reconnection rate and flux return from the nightside.

In steady state, a fairly uniform distribution of reconnection gives rise to the expectation of a poleward component of flow over most of the dayside. Localisation of the reconnection suppresses the poleward component in other sectors. Comparison of these models with the diurnal flow variation recorded by the SABRE radar indicated that the average daily flow pattern or the low frequency component of the flow pattern over a given day is well described by a simple balanced two-cell convection pattern, symmetrical about ~ 12 MLT, approximately centred on the geomagnetic pole, and with a limited reconnection "throat".

Once the dayside reconnection rate exceeds the rate at which flux is returned to the dayside, magnetopause erosion occurs and the polar cap area increases in response. Either localised erosion or uniform polar cap expansion gives rise to equatorward flow components at local times away from the reconnection "throat". We presented observations showing an equatorward component to the afternoon auroral zone flow, consistent with that expected during an erosion event. Ancilliary data show that in this event the polar cap expansion was uniform (see Chapter 4). However, we argued that under certain conditions localised perturbations to the generally circular polar cap could occur.

It is this author's opinion that the generally circular geometry of the polar cap (Meng et al., 1977) indicates that the magnetosphere cannot readily support the pressure gradients

arising from localised erosion. Instead localised distortions to the polar cap probably only occur as a result of geomagnetically active, dynamic events involving large induction electric fields. The most explosive magnetospheric phenomenon is the substorm. We note that localised perturbations to the nightside auroral oval whose poleward edge delineates the polar cap boundary are frequently observed at substorm onset and propose that this observation is the nightside equivalent to the dayside erosion process considered above. Magnetic flux erosion of the nightside polar cap occurs for a short period after substorm onset before the magnetosphere-ionosphere system reacts to the enhanced nightside reconnection rate and the polar cap erosion is arrested and a nightside "flux return event" occurs. Flux moves toward the dayside as the magnetosphere reconfigures and the polar cap boundary relaxes back by a longitudinal expansion of the polar cap bulge. Such a sequence then resembles the poleward auroral leap and westward travelling surge and eastward auroral break-up observed during the substorm expansion phase (Akasofu, 1977).

CHAPTER 3

PRESSURE-DRIVEN MAGNETOPAUSE MOTIONS AND ATTENDANT RESPONSE ON THE GROUND.

3.1. Preface.

The work presented in this chapter forms the content of a published paper (Farugia et al., 1989). It has been extended in a subsequent publication (Freeman et al., 1989) by incorporating data from an equatorial ground magnetometer to demonstrate clearly that magnetospheric compressional wave energy can couple into field guided Alfvén waves to drive the observed plasma motions in the ionosphere.

3.2. Introduction.

This chapter concerns the mapping of field and plasma disturbances from the solar wind to the outer edge of the terrestrial magnetosphere and then to the high latitude ionosphere and to disturbances recorded on the ground below. We use data from a serendipitous arrangement of spacecraft and ground stations to trace the movement of the magnetopause in response to changes in solar wind conditions and then to examine the origin of a series of rapid (minute time scale) perturbations recorded in high latitude magnetograms in the same general (afternoon) local time sector as the spacecraft.

The relationship between solar wind conditions (velocity, pressure and magnetic field strength and direction) and magnetospheric and ionospheric motions is of fundamental importance in solar-terrestrial physics. The magnetopause is a free boundary between the solar and terrestrial plasma regimes. In this chapter we examine how it responds to changes in external pressure (dynamic, field, or gas). The overall response of the magnetospheric cavity to a pressure rise from outside is to shrink, but the detailed behaviour is complex. The magnetosphere and ionosphere are a coupled system which may oscillate and may also exhibit a large transient response when departures from equilibrium occur.

In steady state, the mapping of plasma motions is straightforward: the flow at each point on the flux tube has to be just such that the (frozen-in) magnetic field does not change with time. The flow field and the electric field are related by the frozen-in field condition

$$\mathbf{E} = - \mathbf{V} \times \mathbf{B} \quad (3.1)$$

Thus magnetic field lines are electrostatic potentials and the mapping of flow from magnetosphere to the ionosphere depends only on the geometry of the (steady) background field.

In steady state, ion-neutral collisions in the ionosphere absorb momentum from the flow system and an overall distribution of magnetic stress must be set up to maintain the ionospheric flow. Parallel current flow is a natural concomitant (see e.g. Southwood and Hughes, 1983).

In unsteady situations, matters are more complicated. In the extreme case where magnetospheric flows change so rapidly that momentum cannot be supplied to the ionosphere fast enough for the ionospheric flow to keep up with the magnetospheric motion, the ionospheric part of flux tubes does not move and the ionospheric electric field is negligibly small. The effect is sometimes called 'line tying' (see e.g. Coroniti and Kennel, 1973) and the ionosphere looks as if it is perfectly conducting.

On intermediate time scales, the ratio of ionospheric electric field to magnetospheric electric field is generally lower than the steady state ratio. On such time scales, the magnetic stress is not evenly distributed along the magnetic field lines and magnetohydrodynamic waves propagate back and forth along closed field lines (Southwood and Hughes, 1983), whilst standing Alfvén structures form where tubes are open (see e.g. Wright and Southwood, 1987). As in steady state, field-aligned currents are expected to flow. The transverse or Alfvén magnetohydrodynamic wave mode is the only mode that carries field-aligned current and thus will normally be involved. The mode has the special property of being strictly field guided (in a uniform plasma). Alfvén mode motion localised to given flux tubes in the magnetosphere at a given time will remain so localized at later times. There will be a similar localization in the ionosphere.

Any sudden surge or rapid change in magnetospheric flow conditions will lead to magnetic stress imbalance between magnetosphere and ionosphere regardless of the precise source of the flow change. One case which has excited a lot of recent interest has concerned the imprint that reconnection at the Earth's magnetopause might leave on the ionosphere. In particular, the ionospheric signature of flux transfer events (FTEs; Russell and Elphic, 1978), which have been commonly attributed to localized reconnection taking place in a short-duration (of order two min or less), bursty manner, has recently received much attention.

Early studies of the magnetic field in FTEs (Cowley, 1982; Paschmann et al., 1982; Saunders et al., 1984) established the presence of a net field-aligned current of a few $\times 10^5$ A flowing into or being drawn out of the ionosphere. Later theorizing (Southwood, 1985; 1987) and case studies (Rijnbeek et al., 1987) suggested that bipolar currents flow along the flanks of a central core of reconnected flux. Mapping the pattern down to the ionosphere gave a prediction of the electric field, current and localized flow in the ionosphere. Using these ideas, McHenry and Clauer (1987) modelled the expected response in magnetometers located at high latitude on the ground. Amongst their important results they predict that a ground magnetic observatory should detect a bipolar magnetic field perturbation in the North-South direction for an FTE perturbation moving poleward over the station. The sense of the signature changes depending on model and observer's position. The

scale size of the perturbation is 1-2 (depending on model) times the characteristic dimension of the reconnected flux tube's foot in the ionosphere. Typically, this is expected to be 100-200 km, but could be very different since it depends on, amongst others, the field topology of flux transfer events (Southwood et al., 1988; Scholer, 1988) and the magnetosheath field strength (Freeman and Southwood, 1988a).

A number of transient signatures recorded at low altitudes or on the ground have been imputed to localized reconnection at the Earth's magnetopause. An early report by Lanzerotti et al. (1986) identified a signature at one ground station whose characteristics matched fairly well those predicted by one of the current systems noted above. Subsequently the interpretation was somewhat weakened (Lanzerotti et al., 1987). Todd et al. (1986) reported short-duration flow bursts from the Eiscat radar system and showed these to be consistent with the Southwood (1987) model of impulsive reconnection. In a further study (Todd et al., 1988) pulsations following a poleward-moving flow burst were also seen. Certain types of pulsations have been found to be positively correlated with a southerly IMF orientation (Gillis et al., 1987) and hence, indirectly, with FTEs since these strongly correlate with southward magnetosheath and interplanetary field components (Rijnbeek et al., 1984; Berchem and Russell, 1984; Southwood et al., 1986).

There are, however, other causes besides reconnection for rapid changes in the magnetospheric flow conditions. For example, sudden changes in the solar wind dynamic pressure will move the magnetopause and thus also the plasma inside the magnetosphere. It is likely that any sudden change would also have oscillations directly associated with it. Furthermore, there may be sources of oscillations in the magnetosphere other than transient changes in ionospheric-magnetospheric stress balance. For example, surface waves can be caused by the Kelvin-Helmholtz instability on the boundary (Southwood, 1968). Therefore it is important to distinguish between those signatures due to impulsive reconnection and those due to other causes.

Caution in identification of ground signatures of FTEs has recently been urged (Friis-Christensen et al., 1988; Potemra et al., 1989). Potemra et al. (1989) study a pulsation event recorded by the Eiscat cross magnetometer array. The two types of response identified, a 5 min period 'ringing' and a 10 min driven oscillation, are attributed to variations in solar wind dynamic conditions, although the possibility of an IMF-controlled origin could not be excluded completely. Friis-Christensen et al. (1988) provide strong evidence for the presence of a signature like that predicted in the model presented by Southwood (1987) but at the same time provide compelling evidence that the source is not an FTE. Using recordings from a latitudinal chain of magnetometers in Greenland, they infer a large-scale (about 10^3 km across) travelling twin vortex. The speed of motion of the pattern across the

array (of order 10 km s^{-1}) is, however, inconsistent with what one would expect for an FTE, where the pattern would move at the same speed as the convection speed of the plasma in the centre of the event and would be unlikely to much exceed 1 km s^{-1} (of order the ionospheric sound speed).

The study reported here grew out of a search for high latitude ground signatures of FTE occurrence. Indeed, some of the recordings we present match the predictions for ground signatures of FTEs (McHenry and Clauer, 1987; and references therein). Nonetheless, the occurrence of FTEs at high altitude is not a satisfactory explanation. In this chapter we use a fortuitous conjunction of spacecraft and ground magnetometer data. One spacecraft is in the solar wind and two spacecraft are near the magnetopause, which they cross and re-cross repeatedly. We are able both to measure changes in the solar wind conditions and follow the corresponding magnetopause motions directly. Careful timing of signals establishes a causal relationship between the two. Simultaneously, the high resolution (10 s) ground magnetometer data from a wide baseline range of stations register oscillations of amplitude $\sim 100 \text{ nT}$ and period $\sim 6 \text{ min}$.

In the next section we present a data overview. We show ISEE 1 and 2 spacecraft data for several magnetopause crossings which occurred in quick succession, data related to conditions in the solar wind, and ground magnetometer data at 10 s resolution from 14 high latitude stations. A thorough analysis of the data is then presented in the subsequent section.

A critical parameter to establish is the likely delay time between sites in space and on the ground. We calculate propagation times for a disturbance to reach the subsolar magnetopause, and then relate perturbations recorded at the various sites. By direct observation of the magnetopause boundary motions we deduce that the signals recorded on the ground were due to sudden changes of solar wind ram pressure. The response seems to be a function of latitude. On some magnetic shells resonant Alfvén wave oscillations are excited while elsewhere oscillations do not appear or are strongly damped. The signal pattern in the latter case is shown to be similar to signatures predicted by theory for FTEs. However, we conclude that the signals are not associated with reconnection at the magnetopause, and that the agreement with modelled ground FTE signatures is purely coincidental.

3.3. Data Overview.

3.3.1. Solar wind and magnetopause observations.

In this chapter we study a three hour period from 23:30 to 02:30 U.T. on days 252/3 (September 9/10), 1978. During the interval the IMP 8 spacecraft was in the solar wind on the dawn flank of the magnetosphere. Its position in geocentric solar magnetospheric (GSM) coordinates was (9.9, -32.2, 1.2) at 22:00 U.T. and (12.3, -31.9, 2.9) at 02:05 U.T., where distances are given in Earth radii, R_E . ^{Five} min averaged plasma and field data from the IMP 8 spacecraft are shown in Fig. 3.1 for a 5 h interval 22:00 to 03:00 U.T. The panels show from top to bottom : density, n (cm^{-3}); bulk speed, V (km s^{-1}); GSM X, Y, Z components of the interplanetary magnetic field (IMF), and, finally, the total field strength, B (nT).

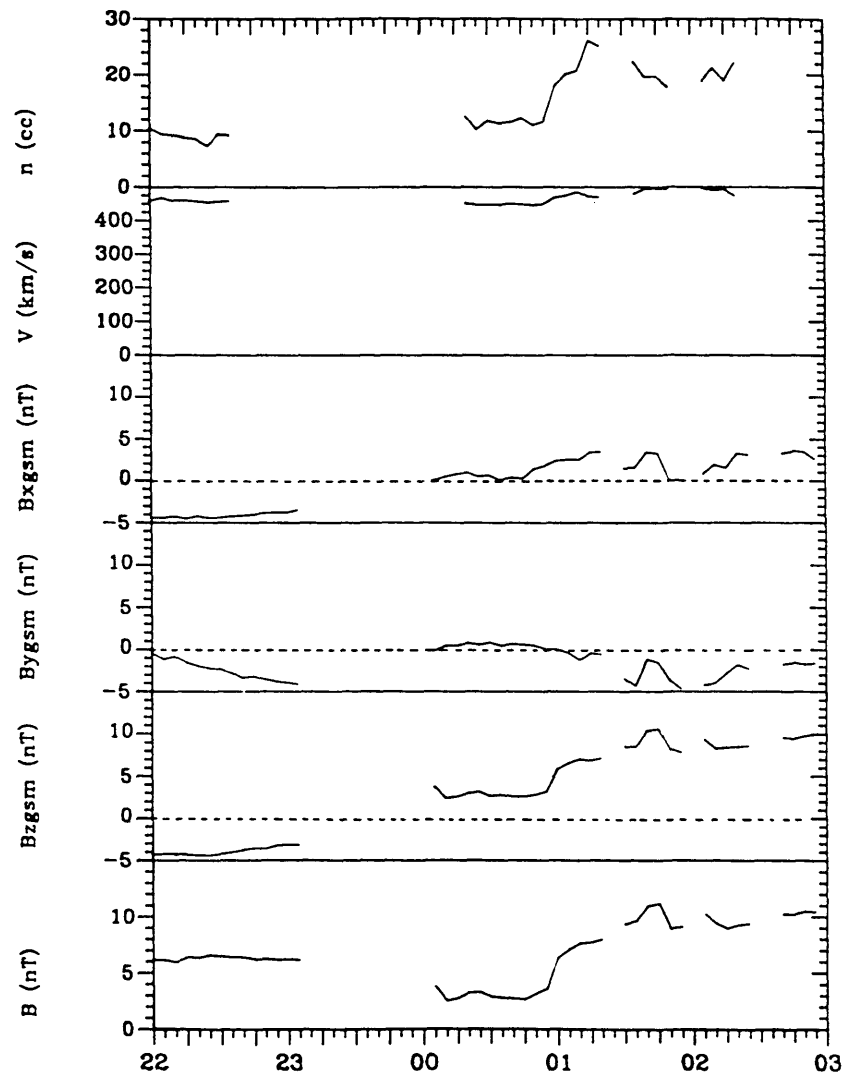


Fig. 3.1. 5 min averaged solar wind plasma and magnetic field data from IMP 8 for the interval 22:00 U.T., Sept. 9, 1978 to 03:00 U.T., Sept. 10, 1978. From top to bottom the panels are: density (cm^{-3}), bulk speed (km s^{-1}), IMF components (nT) in GSM coordinates, and total field magnitude (nT).

Up to $\sim 23:05$ U.T. the data show fairly typical solar wind densities, velocities and field strengths. In the data gap between 23:05 and 00:05 U.T., all three components must have changed sign at least once since they all start zero or positive at 00:05 U.T. but were negative before. B_z is continuously positive from 00:05 U.T. onwards. From 00:05 U.T. to 00:45 U.T. the IMF is fairly steady and primarily northward. At 00:55 U.T. the density increases sharply as does B_z and the field strength. Subsequently there is a further increase in field magnitude. The field remains northward.

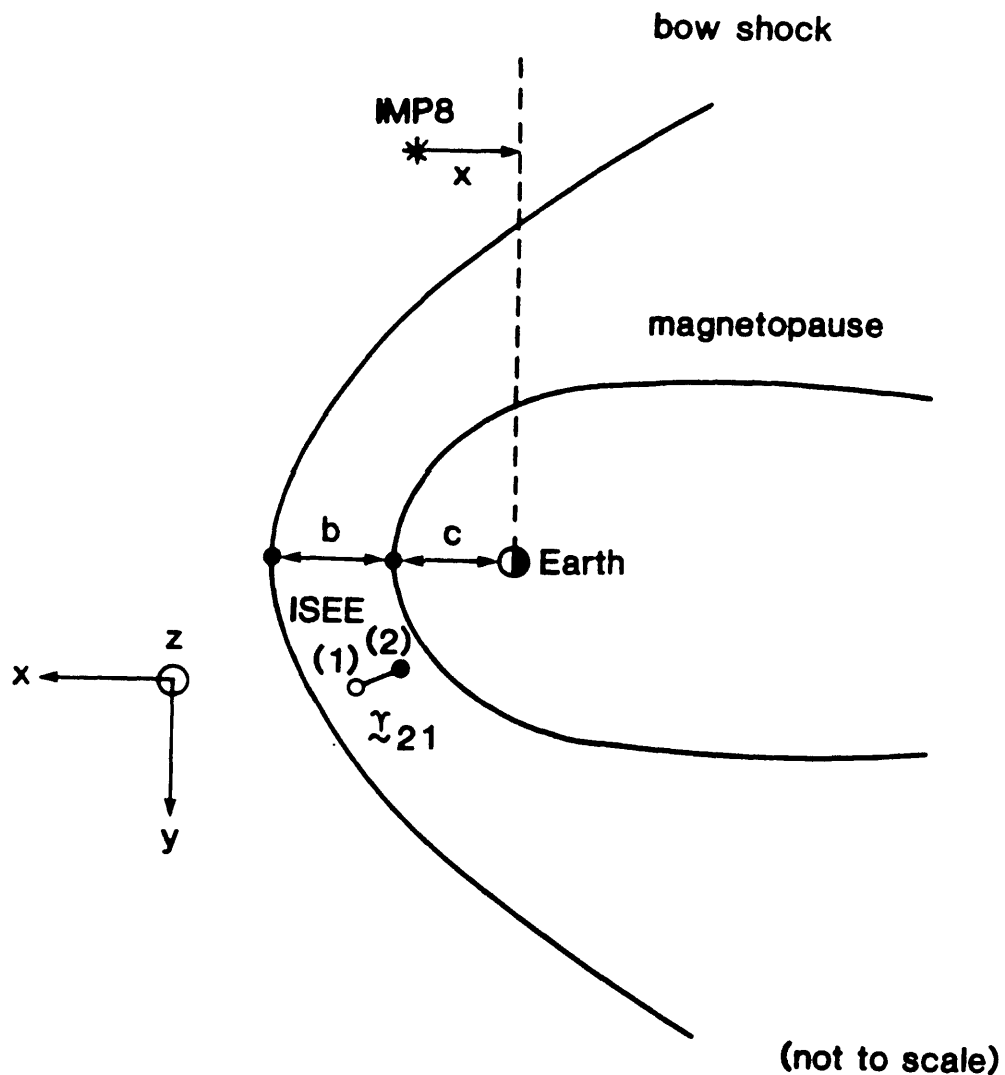


Fig. 3.3. A schematic showing the relative positions of the spacecraft in the ecliptic plane and typical bow shock and magnetopause.

At the same time, the ISEE 1 and 2 spacecraft are inbound, just south of the magnetic equator and in the mid-afternoon local time sector (15:08-15:42 LT). Magnetic field data from the two spacecraft are shown in Fig. 3.2 a-c for the period of interest. The field data of Fig. 3.2 a-c are 12 s averages sampled every 4 s. They are plotted in GSM coordinates, the dark trace corresponding to measurements on ISEE 2. ISEE 1 plasma data (at 100 s resolution) have been used to confirm the identification of the region which this spacecraft is in.

The radial distance, local time and latitude of ISEE 2 are shown at half-hourly intervals underneath the time axis in the figures. ISEE 2 is the leading spacecraft and is displaced earthward and westward of ISEE 1. At 01:00 U.T. the GSM components of the spacecraft separation vector from ISEE 2 to ISEE 1, r_{21} , were (1599, 916, 280) km. The total distance between the spacecraft increased monotonically from 1600 km (at 23:30 U.T.) to 2240 km (at 02:30 U.T.). Fig. 3.3 illustrates the spacecraft positions projected on the GSM X-Y plane. A typical magnetopause and bow shock location are shown. The angle of the ISEE 2 trajectory with respect to the GSM X-Y plane decreased steadily from -3° to -9° . The separation vector r_{21} also lay close to this plane.

Fig. 3.2a shows that the spacecraft start the interval in the magnetosheath, where the field points south and west (negative B_y). ISEE 2 makes what are possibly partial entries into the magnetosphere at times indicated by the guidelines at a1, a2, a3 in Fig. 3.2a. From the bipolar B_x variation, a2 is probably an observation of a flux transfer event (FTE). At this time the magnetosheath B_z component is negative; surveys (Rijnbeek et al., 1984; Southwood et al., 1986) have shown that FTE occurrence is highly correlated with southward sheath field components.

The guideline a4 marks where the field turns northward. However, this is not an entry into the magnetosphere. Rather, we interpret the direction change as the sheath response to the change in IMF orientation detected in the IMP 8 data. Precise timing comparison with IMP 8 is precluded by a data gap (see Fig. 3.1). ISEE 1 plasma data (not shown) retain the characteristics of the magnetosheath across a4, and reveal that the sheath density increased suddenly at a4 from values $n \sim 30 \text{ cm}^{-3}$ to $n \sim 50 \text{ cm}^{-3}$, a value which persists until ISEE 1 encounters the magnetosphere at $\sim 00:42$ U.T. The magnetosheath field fluctuations have a different character after a4 to the disturbances seen before, being predominantly in the B_z component and containing higher frequency components. The spacecraft remain in the new field regime for about half an hour. The mean field remains low until ISEE 2 detects magnitudes comparable with those encountered in the magnetosphere proper at about 00:40 U.T. The perturbations seen in the ecliptic plane at a1-a3 are usually precursors of a magnetopause crossing when reconnection is ongoing. Evidently

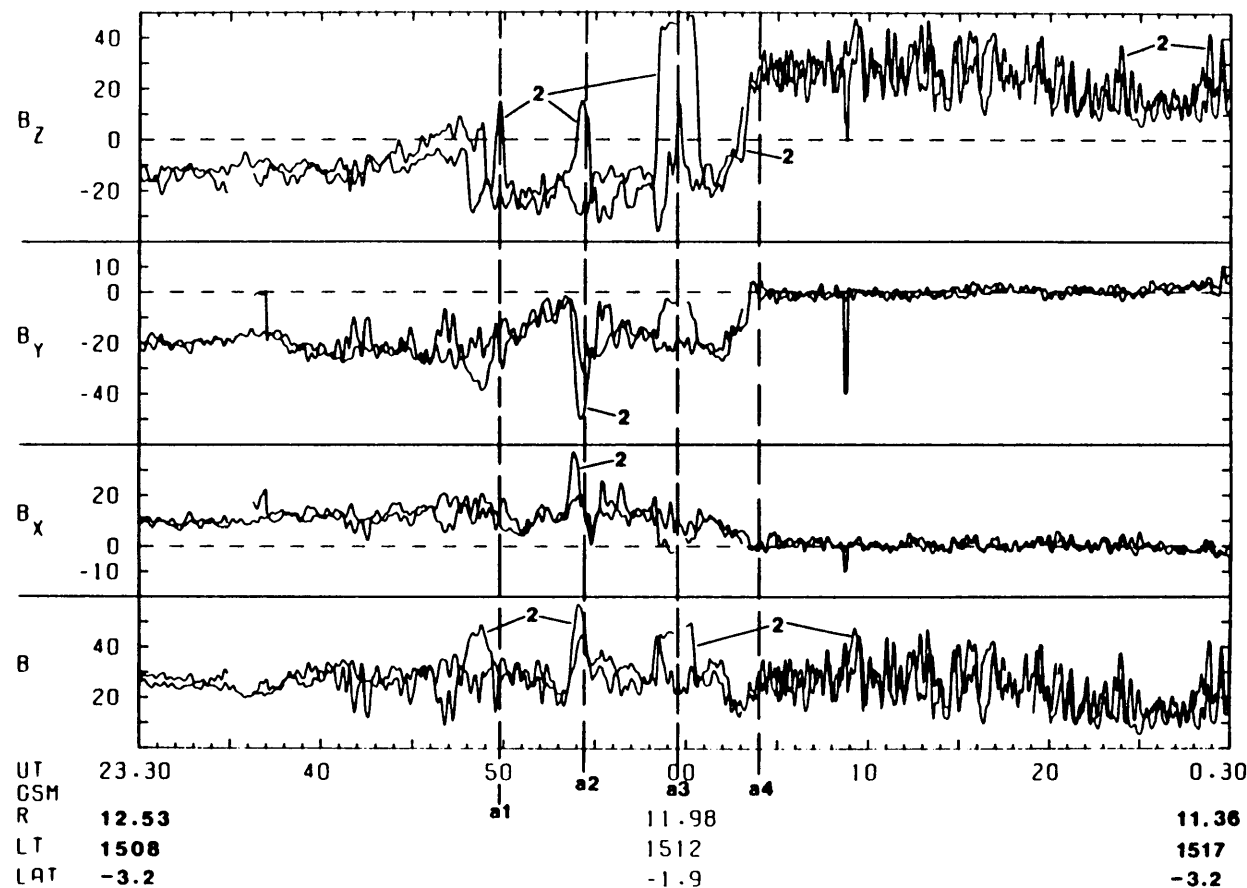


Fig. 3.2. Magnetic field data in GSM coordinates for the inbound pass of the ISEE 1 and 2 spacecraft. ISEE 2 measurements are the heavier trace. Position data for ISEE 2 are given at the bottom of each plot at 30 min intervals. Vertical guidelines a1-a10 are explained in the text.

Fig. 3.2a: ISEE magnetic field data, 23:30 - 00:30 U.T., September 9/10, 1978.

the northward magnetosheath field orientation after a4 has switched off such variations in a very effective way. Fortuitously for this observation, the boundary has been moved away from the spacecraft by the dynamic pressure increase coincident with the field reorientation.

Fig. 3.2b shows encounters with the magnetosphere. From plasma data (not shown) ISEE 1 crossed the magnetopause at 00:47 U.T. (a6), where it encountered the much stronger, less disturbed field of the magnetosphere. The magnetosheath and magnetosphere fields are almost exactly parallel, though of unequal strength. ISEE 2 appears to have encountered the strong field region about 5 min earlier (a5), though the external field orientation makes precise identification of this magnetopause crossing somewhat problematic.

The magnetopause is unlikely to be moving much as the spacecraft enter the magnetospheric field; the ISEE 1 and ISEE 2 field increases are well separated in time. Using the speeds of the spacecraft and their separation at this time we can infer that the magnetopause was not moving faster than 1 km s^{-1} in the radial direction.

The spacecraft remain in the magnetosphere for ~ 20 min, exiting abruptly at a7 (01:05 U.T.), the trailing spacecraft first. In contrast with the entry, ISEE 1 and 2 exits are very closely spaced in time. Inter-spacecraft timing gives an inward magnetopause speed estimate of $\sim 90 \text{ km s}^{-1}$. (For comparison, one can note that the Alfvén speed for a 50 nT field in a 100 cm^{-3} plasma is $\sim 100 \text{ km s}^{-1}$; the boundary speeds deduced here and later in the paper are comparable to this value.)

A study of Fig. 3.2c shows that both spacecraft started in the sheath at 01:30 U.T. and were firmly in the magnetosphere by 02:10 U.T. In between these times each spacecraft crossed the magnetopause boundary five times. We determine this from plasma data for ISEE 1 and the magnetic field data shown in Fig. 3.2c; using the plasma data we can determine which region ISEE 1 was in, and using the magnetic field data we can determine whether ISEE 2 was in the same region as ISEE 1. Whenever there is a large magnetic shear between ISEE 1 and 2, e.g. at $\sim 01:44$ U.T., we infer the spacecraft to be on opposite sides of the magnetopause. From this analysis we infer that both ISEE 1 and ISEE 2 were in the magnetosphere at a8 (01:46 U.T.) and a9 (01:57 U.T.) and in the sheath at $\sim 01:51$ U.T. and at a10 (02:02 U.T.). Overall, we conclude that ISEE 2 (nearest the Earth) entered the magnetospheric field during the large transverse (B_x , B_y) perturbations at 01:43 U.T. and exited into the magnetosheath at 01:48 U.T., reentering the magnetosphere at 01:54 U.T. In the vicinity of a8, ISEE 1 grazed the magnetospheric field, makes a pair of brief entries into this field again either side of a9, and enters the terrestrial regime finally at 02:03 U.T. just after a10.

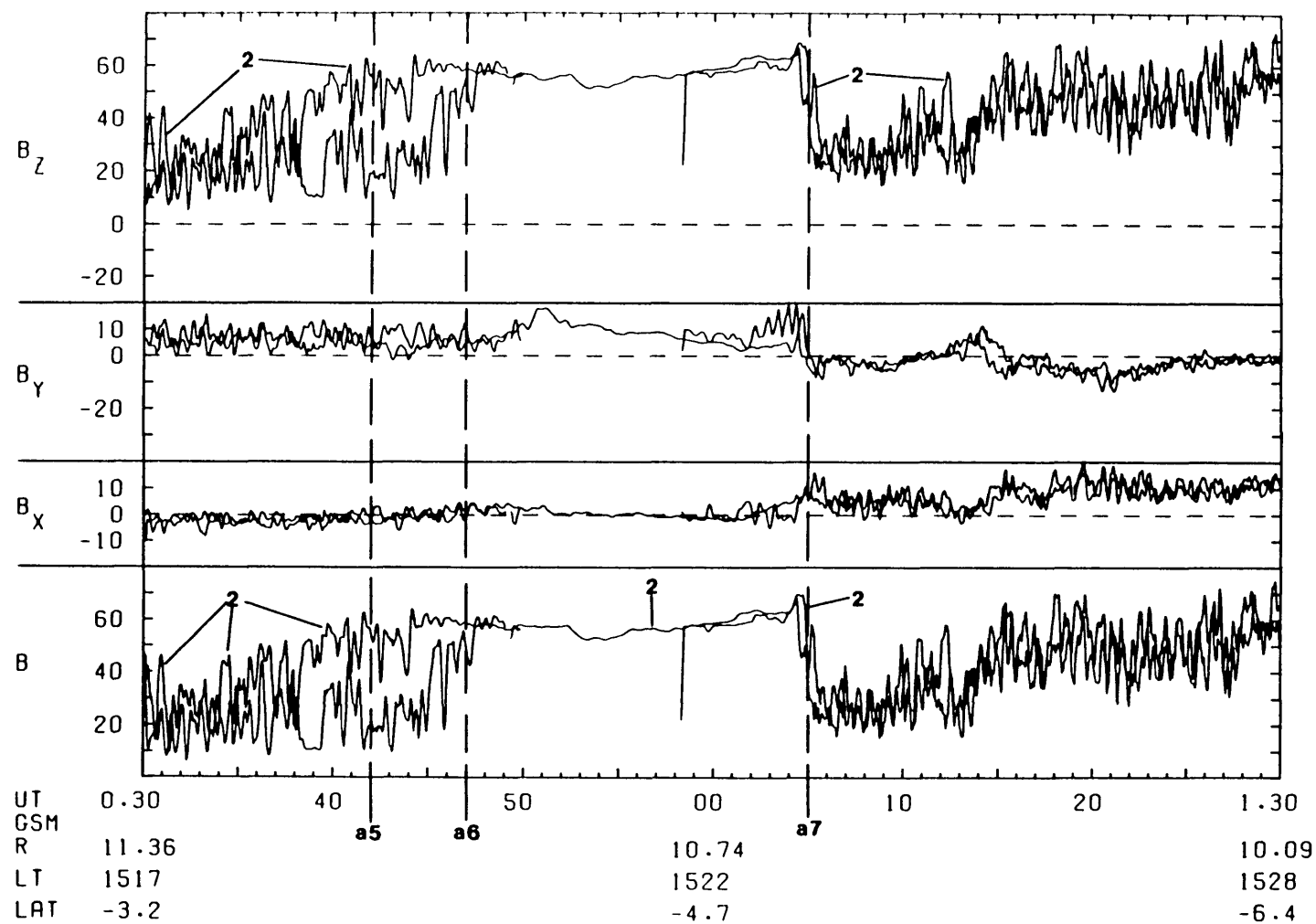


Fig. 3.2b: ISEE magnetic field data, 00:30 - 01:30 U.T., September 10, 1978. See Fig. 3.2a for details.

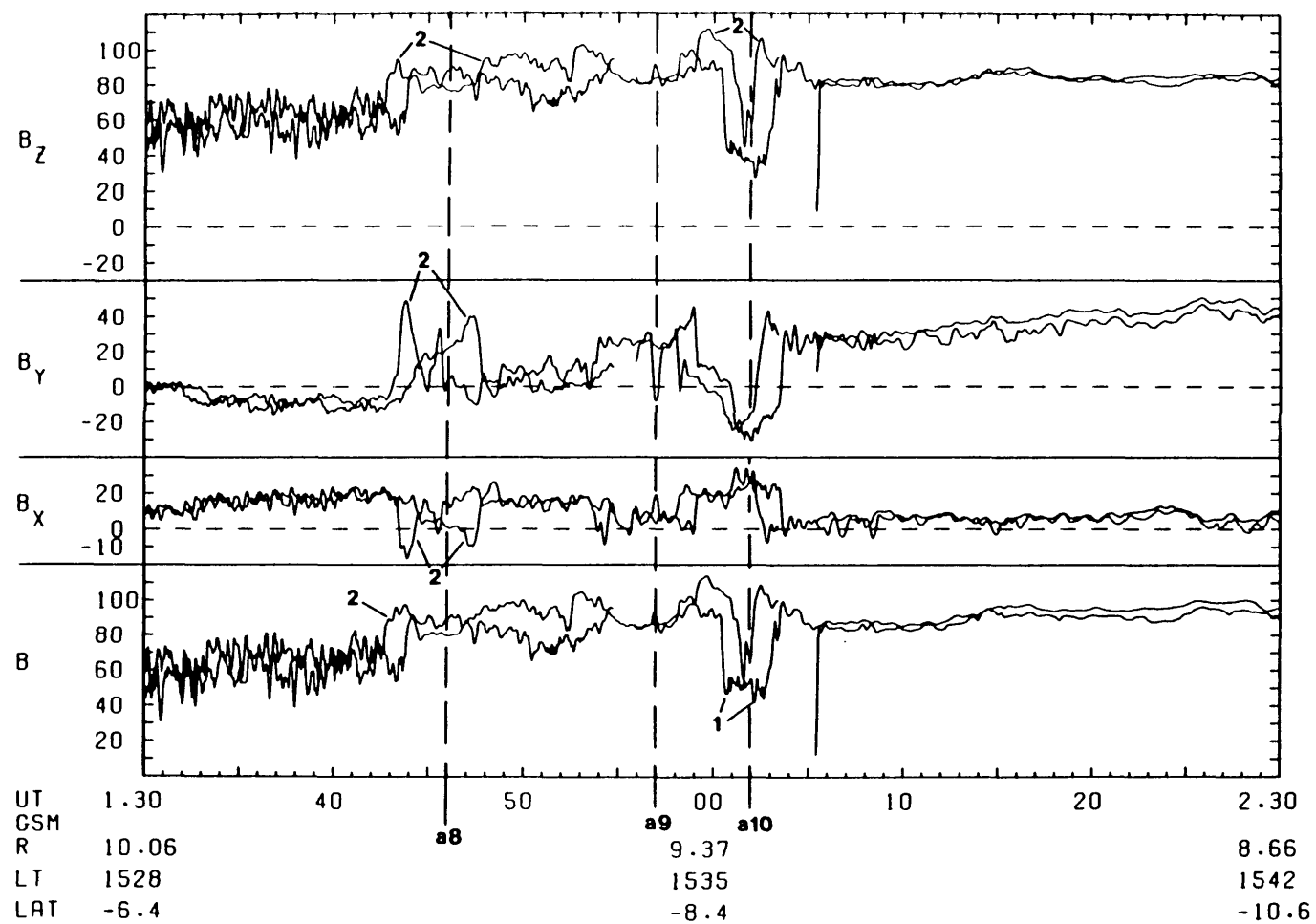


Fig. 3.2c: ISEE magnetic field data, 01:30 - 02:30 U.T., September 10, 1978. See Fig. 3.2a for details.

During these crossings there are some interesting points to note. In the period 01:48 - 01:54 U.T. when we identify both spacecraft to be in the sheath, the field strength is larger than recorded in both previous and later sheath encounters. Our interpretation that the larger field is indeed that of the magnetosheath is supported by the fact there is a corresponding proportionate rise (about 30%) in the total field value recorded 7.5 min earlier at IMP 8 upstream in the solar wind (see Fig. 3.1, bottom panel). The sheath field fluctuations evident in the earlier, weaker field have lower amplitude at this time. Also the sustained difference in the field magnitude measured at the two spacecraft is anomalous for a circumstance where both spacecraft are believed to be on the same side of the magnetopause. The gradient detected is larger than that detected later in the magnetosphere. Similar field gradients were detected for briefer periods in the sheath in the preceding half hour.

The symmetrically nested signatures seen by the two spacecraft which bracket the final encounter with the magnetosheath centered on a10 are notable; using them, we infer an inward followed by an outward radial velocity of 28 km s^{-1} of the magnetopause boundary. There are clear field compressions on exit and on re-entry at a10. In the sheath at ~02:02 U.T., the spacecraft see a field which is weaker than at the last encounter and more strongly westward (i.e. B_y more negative). This is also similar to the IMF behaviour about 7.5 min. earlier (see Fig. 3.1). After a10 the spacecraft are unmistakably in the magnetosphere, which has a northerly and easterly orientation as appropriate for a terrestrial field at this LT sector.

3.3.2. *Ground magnetometer recordings.*

The ground stations used in this study are listed in Table 3.1. The perturbations of the geomagnetic field at 8 ground stations from the Alaska and Churchill chains over the 2.5 h interval from 00:00 U.T. to 02:30 U.T. are shown in Fig. 3.4. Fig. 3.4a-c present the field components in the geomagnetic North-South (X), East-West (Y), and vertical (Z) directions, respectively. Positive values correspond to northward, eastward and downward directions. The data are unfiltered and the box height corresponds to 200 nT. The Universal Time is shown along the bottom of the figure and in each panel is shown the station code, its geomagnetic latitude, and its magnetic local time (M.L.T.) along the time axis. The stations can be seen to be well distributed in latitude and local time on the afternoon side of Earth.

We shall concentrate in this paper on ground signatures detected in the interval from 01:00 U.T. to 02:15 U.T. Shortly after 01:00 U.T. all stations shown detect a perturbation of the geomagnetic field. There are also oscillations evident between ~01:40 U.T. and

Table 3.1 - Ground Magnetometer Stations.

Station	Code	Geomagnetic	Geomagnetic
		Latitude	Longitude
Sachs Harbour	SAH	75.2	266.2
Cape Parry	CPY	73.9	270.9
Inuvik	INK	70.6	266.2
Arctic Village	AVI	68.1	255.3
College	COL	64.8	257.1
Talkeetna	TLK	63.0	256.9
Pelly Bay	PEB	78.7	321.1
Eskimo Point	EKP	71.0	322.4
Back	BCK	67.6	324.4
Gillam	GIM	66.3	324.9
Norman Wells	NOW	69.2	278.8
Fort Simpson	FSP	67.2	287.2
Lynn Lake	LYL	66.0	315.8
Fort Smith	FSM	67.3	299.6

~02:00 U.T., again at all stations (see vertical guidelines). The pulsations commencing near 01:00 U.T. and 01:40 U.T. will be considered separately.

The perturbation at station AVI just after 01:00 U.T. is very closely linearly polarized and it is also continuous for 2-4 cycles. Elsewhere, however, the character of the signal is different and the polarization is more elliptical, e.g. at station SAH. It is interesting to note that the pulsation onsets are at slightly different times at each station, indicating propagation of the disturbance. We analyse this in the next section.

Near 01:40 U.T. pulsations recommence. It is apparent that there occur subsequent impulses to the initial one. For example, at station CPY, which at 01:00 U.T. showed only a half cycle oscillation, the oscillation now appears to persist for several cycles but the second cycle is of a larger amplitude than the first. Looking at the signal at AVI, the pulsations appear in 2 discrete packets with a phase skip of $\sim 180^\circ$ at 01:52 U.T. This suggests that the geomagnetic field is responding to discrete impulses.

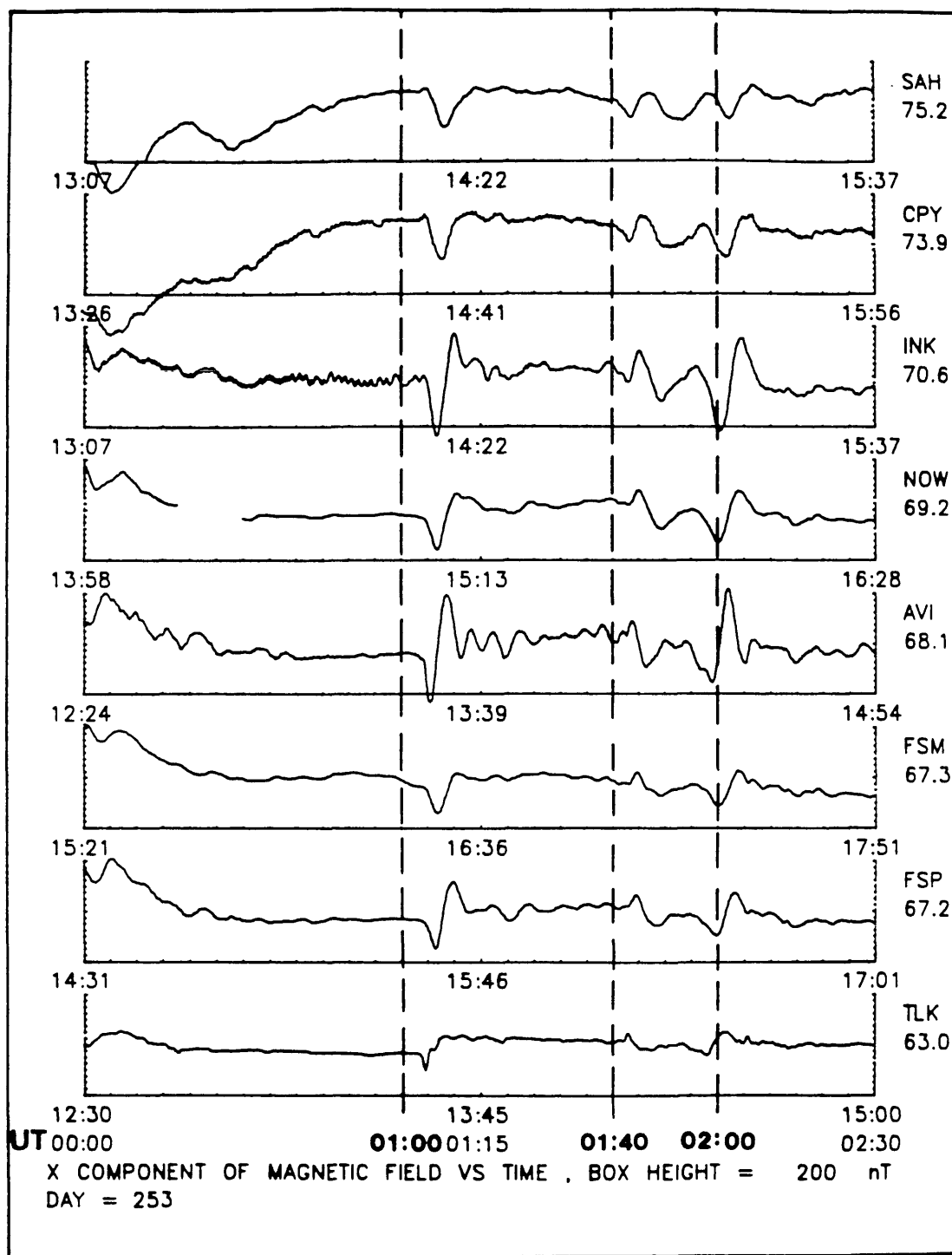


Fig. 3.4. X, Y, Z components of the geomagnetic field from eight northern hemisphere ground stations in the interval 00:00 - 02:30 U.T., Sept. 10, 1978. Station code and geomagnetic latitude are shown to the right of each panel; magnetic local time underneath each panel. Universal Time, field component and vertical scale are given at the bottom of each figure. Vertical guidelines are referred to in the text.

Fig. 3.4a. X component of the geomagnetic field, 00:00 - 02:30 UT, Sept. 10, 1978.

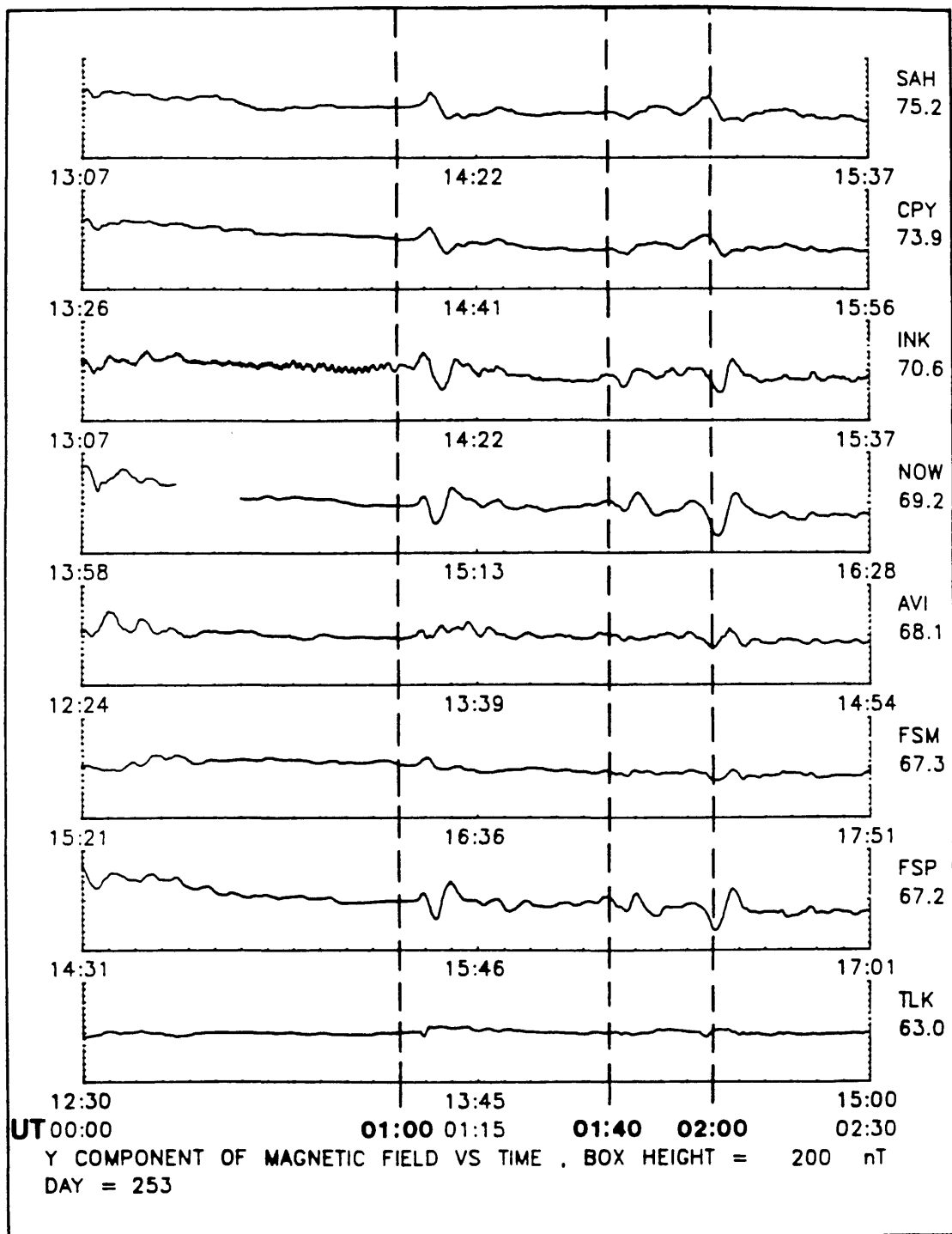


Fig. 3.4b. Y component of the geomagnetic field, 00:00 - 02:30 UT, Sept. 10, 1978. See Fig. 3.4a for details.

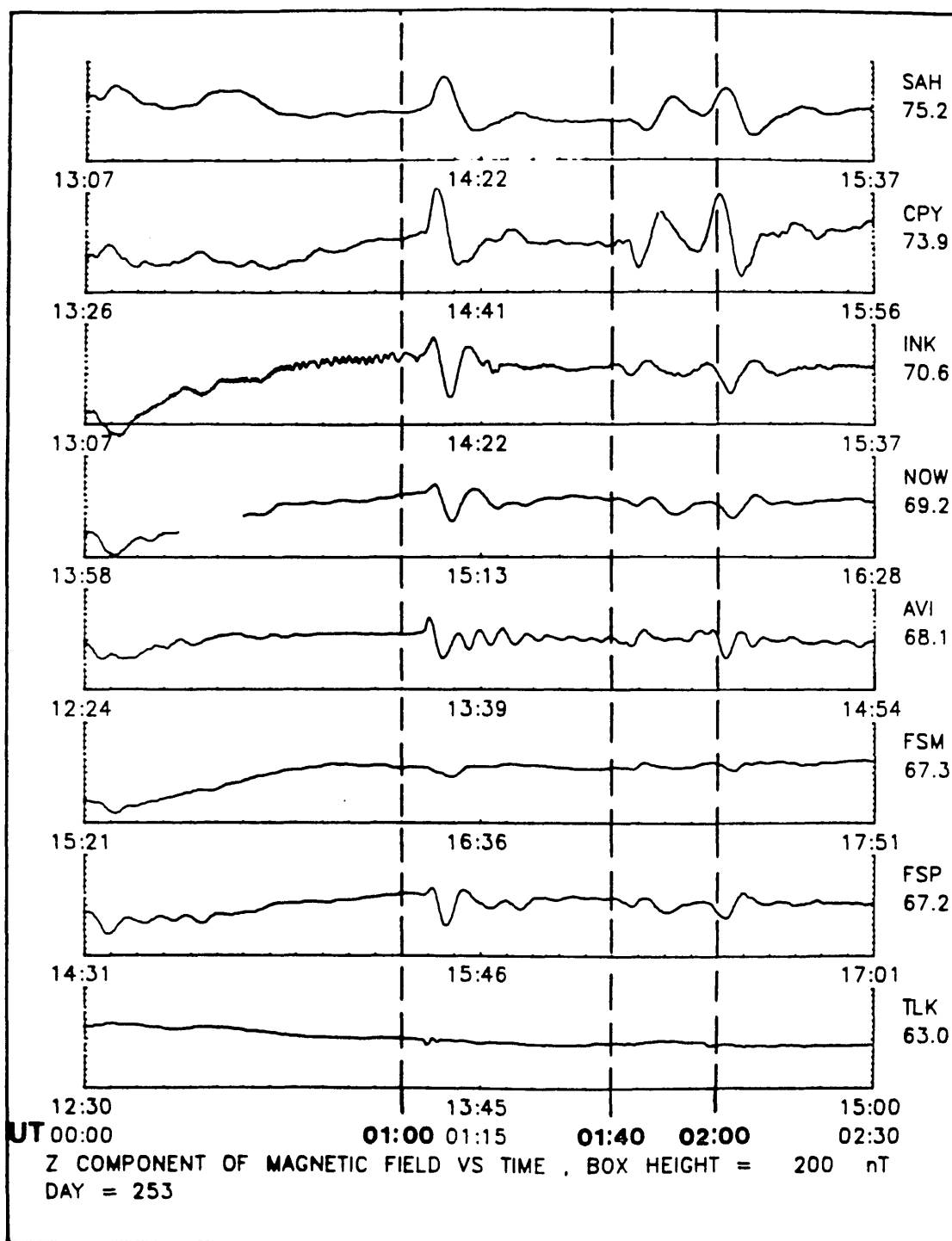


Fig. 3.4c. Z component of the geomagnetic field, 00:00 - 02:30 UT, Sept. 10, 1978. See Fig. 3.4a for details.

3.4. Analysis.

3.4.1. Signal timing and magnetopause motion.

In order to correlate the data from the IMP 8 spacecraft with those from the ISEE spacecraft and the ground based magnetometers, we need an estimate of the time delay for signals to propagate between the observing sites. In the magnetosphere propagation is via one or other of the magnetohydrodynamic wave modes. In the magnetosheath and in the solar wind, any disturbance propagation velocity will be superposed on the velocity of the plasma. In much of the volume of the sheath and everywhere in the solar wind, the plasma convection velocity is much larger than the wave speed; in what follows we shall assume that disturbances in these regions are convected with the plasma and ignore propagation effects other than in the magnetosphere (see Freeman and Southwood, 1988b; and references therein). We also shall assume that the initial disturbance fronts in the solar wind are effectively propagating radially from the Sun.

Consider an interplanetary discontinuity convecting earthwards with the plasma and whose front is perpendicular to the vector V_{sw} . From IMP 8 data (not shown) the solar wind flow velocity vector, V_{sw} , is closely aligned, to better than 6 degrees, with the GSM X-axis. The contributors to the total delay (D) between detection by IMP 8 in the solar wind and reception on the ground or at the ISEE spacecraft are the following : the time for the discontinuity to travel from the nose of the bow shock to the nose of the magnetopause (D_1) minus the time it takes for the discontinuity to reach IMP 8 from the nose of the bow shock (D_2). To this difference must be added the residual delay, D_3 , for the effect of the discontinuity to be detected at the particular recording site (spacecraft or ground-based station). D_3 is either the time for the magnetopause reconfiguration at noon to propagate around to the mid-afternoon local times (in the case of the spacecraft) or the time for a disturbance to travel through the magnetosphere to a flux tube and down the flux tube to the ground observatory.

$$D = D_1 - D_2 + D_3 \quad (3.2)$$

The geometry is as shown in Fig. 3.3. Let b be the distance between the subsolar bow shock and the subsolar magnetopause and c the stand-off distance of the magnetopause boundary from the centre of the Earth. We then have

$$D_1 - D_2 = b/U - (b+c-x)/V_{sw} \quad (3.3)$$

where x is the GSM X-coordinate of IMP 8 ($\sim 11 R_E$) and U the mean plasma velocity in the sheath between the subsolar points on the bow shock and the magnetopause. Using Spreiter and Stahara's (1980) results, we find the average speed, U , should scale as $V_{sw}/8$.

Following Fairfield (1971) we take $b/c \sim 0.33$. We take V_{sw} to be $\sim 480 \text{ km s}^{-1}$ (Fig. 3.1), and the value of c to be $11 R_E$. We then obtain for $D_1 - D_2$ a time difference of 5.5 min. for the discontinuity to travel from IMP 8 to the subsolar magnetopause. Estimating the delay D_3 for the case of the spacecraft is difficult. Using Spreiter and Stahara's (1980) model we infer that it is positive and about 2 min. We estimate D_3 (for the case of the ground stations) to be $\sim 1-2$ min. This is composed of the sum of the times for the fast mode wave to propagate from the magnetopause to the relevant ($L = 7$ for AVI) flux tube (a few tens of seconds) and the Alfvén travel time down the tube (~ 1 min). We obtain for both cases a total lag of about 7.5 min and shall use this figure for the remainder of this paper.

Good evidence for the reasonableness of the estimate of 7.5 min for the delay between IMP 8 and ISEE 1 and 2 is that it is entirely consistent with the rapid inward motion of the magnetopause detected in event a7 at 01:05 U.T. (where the radial velocity was deduced to be as high as $\sim 90 \text{ km s}^{-1}$) being caused by the sharp rise in the solar wind density recorded by IMP 8 between 12:55 UT and 01:00 U.T. Further circumstantial evidence that the association of these two events is correct is offered by the fact that the (noisy) field encountered by the ISEE spacecraft on exit has increased magnitude and an increasingly negative B_y component compared to the values detected earlier. These features are reflected in similar trends in the interplanetary field recorded at IMP 8 as the density rises.

We now take the postulated time lag and use it with the IMP 8 data to predict the variation of the magnetopause position with time. Now the stand-off distance of the subsolar magnetopause is known to scale with the solar wind ram pressure such that

$$C = G / [(n V^2)_{sw}]^{1/6} \quad (3.4)$$

(Schield, 1969). G is a scaling factor which allows for the non-dipolar nature of the field. We shall assume that such a relation describes the magnetopause location at all local times as a function of ram pressure. To determine a value for G at a given local time we need to calibrate using a low latitude magnetopause position recorded during a period in which solar wind parameters had remained steady. In the interval $\sim 00:30$ U.T. to $\sim 00:50$ U.T., before the arrival of the steep density rise, the solar wind parameters measured by IMP 8 are quite steady (we find: $n \sim 11.5 \text{ cm}^{-3}$, $\delta n \sim 0.7 \text{ cm}^{-3}$; $V \sim 448 \text{ km s}^{-1}$, $\delta V \sim 2.0 \text{ km s}^{-1}$; $B \sim 2.8 \text{ nT}$, $\delta B \sim 0.2 \text{ nT}$, the symbol δ denoting the standard deviation). During the 20 min period both ISEE 1 and ISEE 2 (near 15:00 LT) cross the magnetopause just below the GSM equator (Fig. 3.2a, events a5 and a6). We use the radial crossing distance of ISEE 1 ($11.24 R_E$) to obtain a value for G at 15:00 LT, substituting in the equation above the quoted values of solar wind parameters. The numerical value for G thus derived is 129.4 ± 2.6 , where n is measured in units of cm^{-3} , V is in km s^{-1} and the distance C is given in R_E .

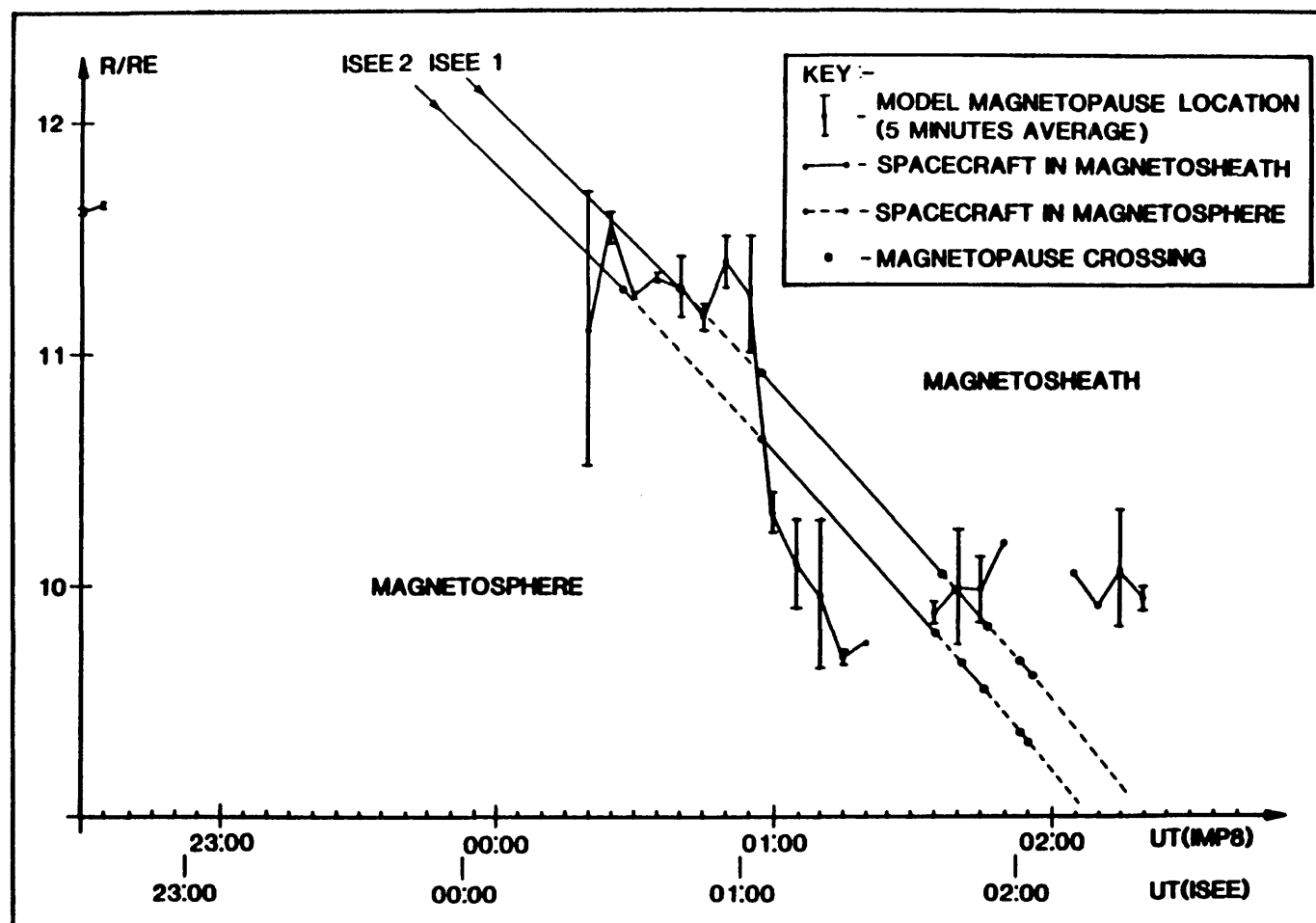


Fig. 3.5. ISEE 1/2 trajectories superposed on a modelled magnetopause location. The expected magnetopause position was obtained from IMP 8 data suitably lagged, as explained in the text. Error bars for these measurements are shown by the vertical lines. Large solid circles on the ISEE trajectories represent observed magnetopause crossings.

Having established a value for G appropriate for the ISEE spacecraft local time range, we can use the formula in conjunction with the IMP 8 spacecraft data to derive a time history for the magnetopause at that local time. The results are shown in Fig. 3.5 which displays the equatorial magnetopause radial distance versus the universal time of the (source) IMP 8 data. Using our estimated lag of 7.5 min, we show also on the abscissa the estimated time of arrival of the corresponding perturbations at the ISEE spacecraft location in the afternoon magnetosheath. Superposed on the plot are the positions of ISEE 1 and 2 with the times of their encounters with the magnetopause ascertained from the data shown in Fig. 3.2 indicated by solid circles.

The agreement between the actual and inferred crossings is remarkably good and suggests that our derived values for the time lag are not far wrong. The spacecraft are always located on the predicted side of the magnetopause whenever the IMP 8 data are available except in one period, namely the brief re-entries into the magnetosheath in the vicinity of 01:50 U.T. (between events a8 and a9). At 01:50 U.T. ISEE 2, the spacecraft closest to Earth is well inside the predicted magnetopause position. Subsequently, ISEE 2 briefly encounters the magnetosheath field again, as does ISEE 1, but at this time a data gap at IMP 8 precludes making a prediction. As we remark later, there are clear ground signatures at this time and we envisage that an increase in solar wind pressure was responsible for both the ground signatures and the incursions of the boundary detected by the ISEE spacecraft.

Shown in Fig. 3.6 is a plot of the effective radial component of the velocity of the magnetopause. The majority of the points have been derived from the 5 min resolution IMP 8 data. We have calculated the velocity by estimating the derivative of the position curve shown in Fig. 3.5. We also include on the plot the values of radial boundary velocity derived from inter-spacecraft timing of crossings where both spacecraft cross the magnetopause at similar times.

The speeds derived from the 5 min position predictions afforded by the IMP 8 data all lie below 10 km s^{-1} except for one value derived during the arrival of the pressure ramp just before 01:00 U.T. The points derived from timing actual spacecraft crossings give velocity estimates that are closer to instantaneous estimates. Despite this the values often are similar to those derived from the 5 min resolution estimates. As we have already reported, there is a very large apparent velocity ($\sim 90 \text{ km s}^{-1}$) recorded during the crossings coincident with the predicted arrival at ISEE of the large density ramp which much exceeds the 20 km s^{-1} derived from the IMP 8 data. Other large instantaneous velocity values are derived during the multiple boundary encounters recorded by the spacecraft between 01:30 U.T. and 02:00 U.T.

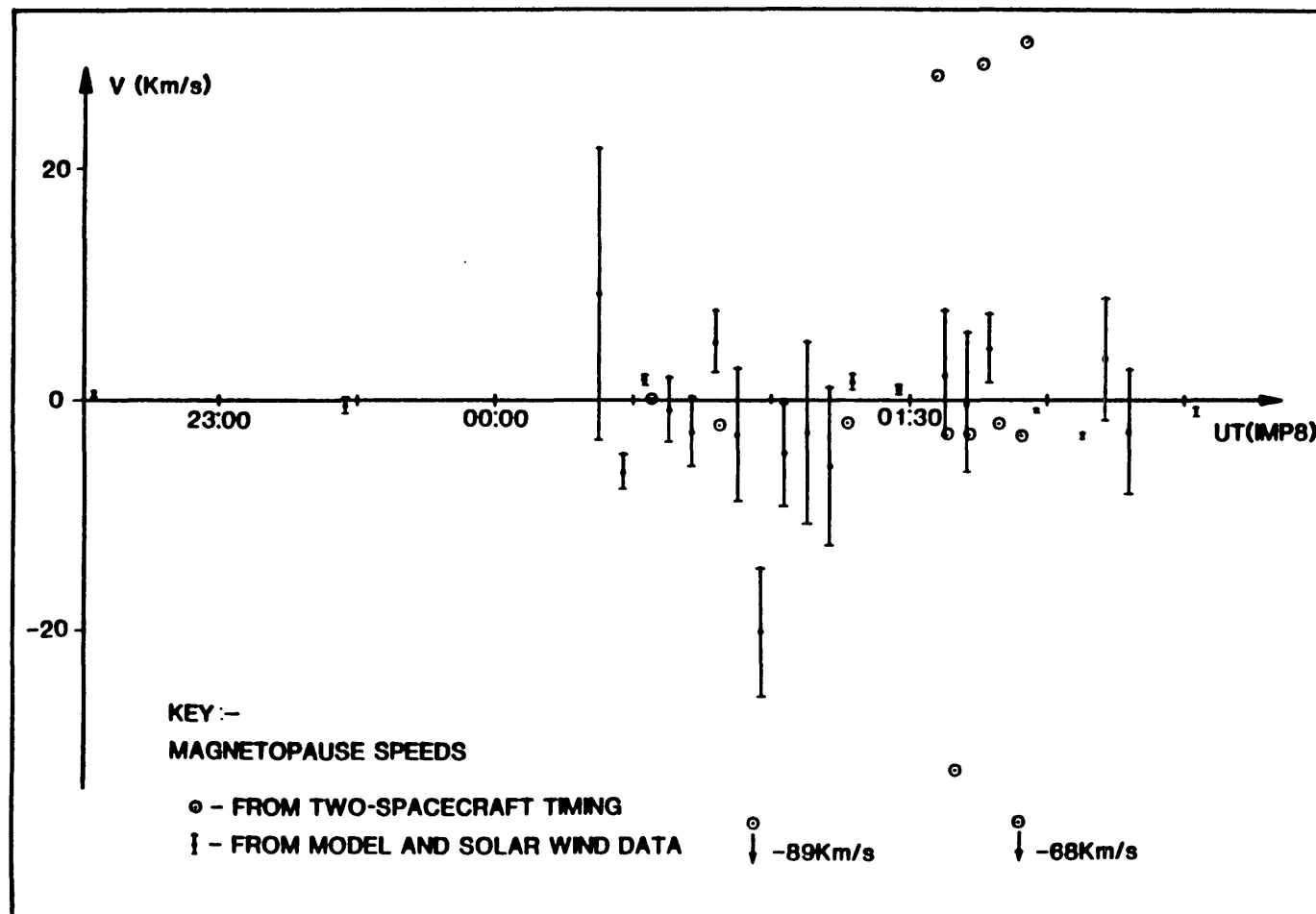


Fig. 3.6. Radial speeds of the magnetopause boundary versus Universal Time at IMP 8. Solid circles with error bars represent those derived from a magnetopause model using the solar wind data. Open circles show speeds calculated from two-spacecraft timing.

It is not surprising that the instantaneous values of velocity exceed those derived from 5 min averaged data. Changes in the external pressure applied to the boundary should produce motion on very short time scales, certainly much shorter than 5 min which, as we have pointed out elsewhere, is comparable to the time for changes to propagate far through the system and thus the time scale for the system to react against the external force.

The instantaneous velocities recorded are not outside the range expected given the size of the changes in the solar wind dynamic pressure recorded at IMP 8. To illustrate this, consider a free planar boundary subjected to a sudden change in the dynamic pressure due to a change in density on one side with a perfectly compressible fluid on the other. Assuming specular reflection, the boundary would move with a velocity given by

$$V_b = V_{sw} (1 - (n_0/n_1)^{1/2}) \cos \phi$$

where n_0 and n_1 are the density before and after the increase respectively, and ϕ is the angle between the solar wind velocity vector and the magnetopause normal. Let us now use the values of density on either side of the ramp recorded near 01:00 U.T. At 00:55 U.T. the density at IMP 8 is $n_0 = 11.7 \text{ cm}^{-3}$, $V_{sw} = 449 \text{ km s}^{-1}$. 5 min later, $n_1 = 18.1 \text{ cm}^{-3}$ and $V_{sw} = 469 \text{ km s}^{-1}$. For this local time we estimate $\phi = 30^\circ$, using the gas dynamic model of Spreiter and Stahara (1980). The argument gives $V_b = 78 \text{ km s}^{-1}$. The level of agreement with the deduced instantaneous value from the inter-spacecraft timing (89 km s^{-1}) is reasonable. Also one may invert the argument and note that the derived velocities shown in Fig. 3.6 generally lying in a band between $\pm 5 \text{ km s}^{-1}$ can be produced by relatively minor changes in pressure.

3.4.2. Ground response to solar wind ram pressure changes and magnetopause motion.

Fig. 3.7 is a composite of several plots. Using the axis on the far left, we show the quantity $(nV^2)_{sw}$ derived from the IMP 8 data. The bar (labelled “reference”) marks the period when the steady conditions were used to calibrate the formula used to predict the magnetopause position. Also shown are the instantaneous magnetopause velocities derived from ISEE 1 and 2 boundary crossings. (Note that the scale has been inverted with respect to that shown in the previous figure; inward velocity is shown measured positive.) Finally, the inset at the top gives the X-component (North-South) of the geomagnetic field recorded at AVI, at 68.1° N , again plotted with a 7.5-min time lag with respect to the solar wind data. The station AVI (Arctic Village) was chosen for display because it showed the clearest oscillatory response to the initial pressure impulse (see Fig. 3.4).

The most clear feature is that the start of the oscillations here, at 01:04 U.T., and hence those of the other stations as well (cf. Fig. 3.4), coincides with the sudden pressure increase.

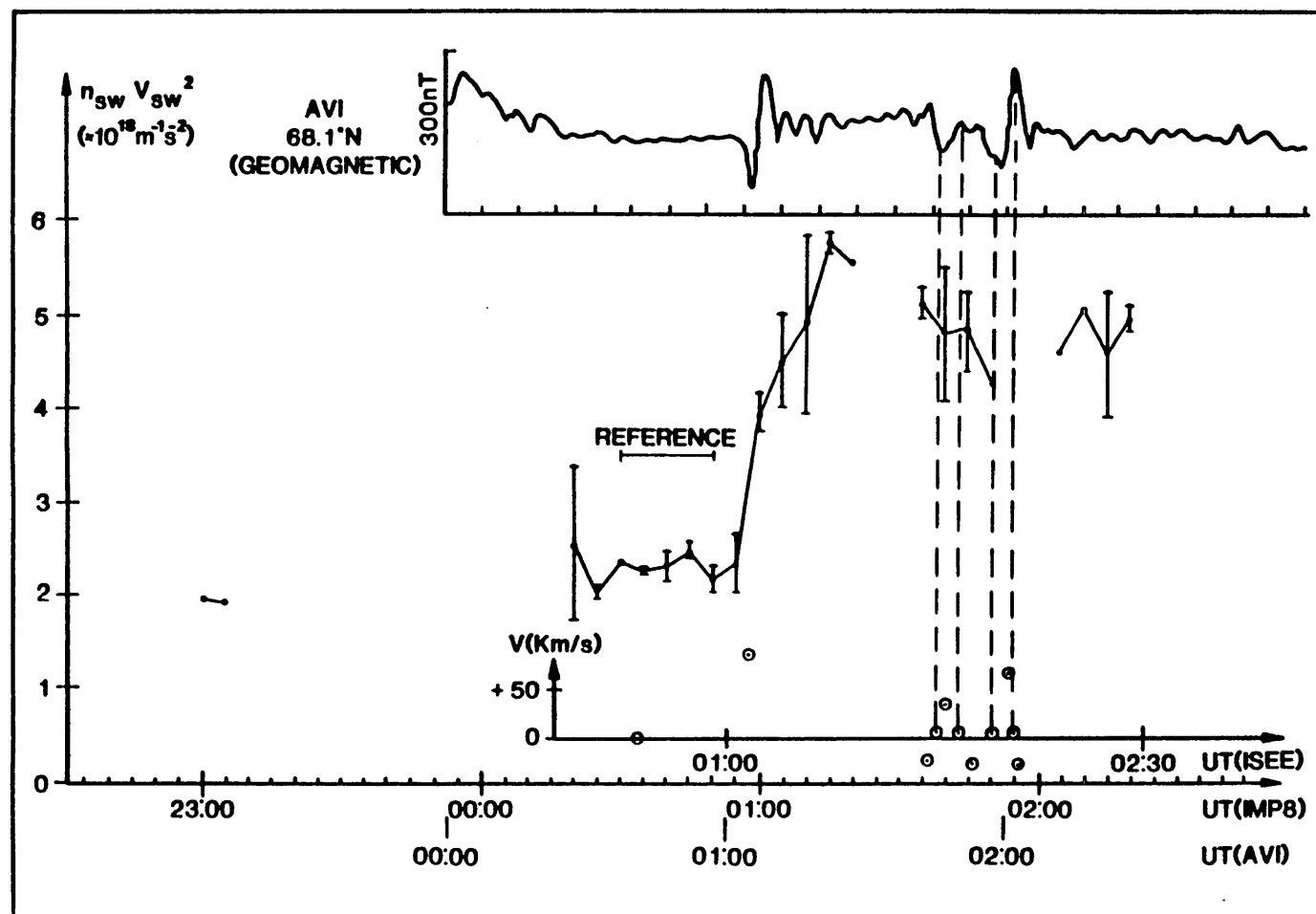


Fig. 3.7. The solar wind ram pressure as a function of Universal Time at IMP 8. The interval marked 'Reference' corresponds to the period of steady solar wind ram pressure. The inset shows the X component of the geomagnetic field at AVI with a lag as derived in the text. The dashed vertical lines relate observations on the ground to measured magnetopause speeds (V ; positive inwards). The latter are shown by open circles and are also lagged.

It seems likely that, in association with the rapid inward boundary motion recorded by the ISEE spacecraft, oscillations have been excited not only in the magnetosphere but also at the field line feet in the ionosphere.

Further oscillations resume about 40 min later. Do these have the same origin as the earlier one? The first point to be made is that the oscillations appear to be occurring when the magnetopause mean motion is outwards and the dynamic pressure is decreasing. Hence, if the sources of the two sets of oscillations are analogous, they resemble transients of the system excited simply by changes in equilibrium conditions rather than being associated specifically with increases in the dynamic pressure exerted on the magnetosphere.

Secondly, the oscillations all fall within a period when the magnetopause was inferred to be oscillating, as the derived velocities in the lower plot show.

To assess this further we obtain the velocity profile of the magnetopause from the position and times of the ISEE 1 and 2 boundary crossings, also shifted by 7.5 min. The oscillations of the boundary agree very well with the oscillations on the ground. Whenever the ground magnetic field is at a temporally stationary point, the measured instantaneous magnetopause speed is close to zero. Such instances are labelled by the dashed vertical lines. When the ground magnetometers detect a rapid change in the Earth's magnetic field with time, the magnetopause was known to be moving rapidly. In particular, the last large excursion of B_x is well correlated with the in-out motion of the magnetopause at ~02:00 U.T. (a10 in Fig. 3.2). We thus conclude that the ground signatures seen between 01:04 U.T. and ~ 02:05 U.T. are due to magnetopause motion, in turn brought about by changes in the solar wind's dynamic pressure. We have observed the ground response to, first, a sudden magnetospheric compression (at ~01:00 U.T.) and, subsequently, a sustained 'rattling' of the magnetospheric cavity (~01:40-02:05 U.T.)

3.4.3. Ground signatures of FTEs ?

The only evidence of flux transfer event activity seen by ISEE 1/2 in the period we study was in the early stages when the IMF and sheath field were southward, the orientation propitious for reconnection. Measurement of the sheath field and the lagged solar wind field show a strongly, almost due, northward orientation throughout most of the period of interest here and, in particular, the ground signatures we have studied occur when the field exterior to the magnetosphere is almost purely northward. However, some of the signatures recorded in the magnetometers bear a strong resemblance to predictions of the signature produced on the ground by the occurrence of an FTE at high altitude.

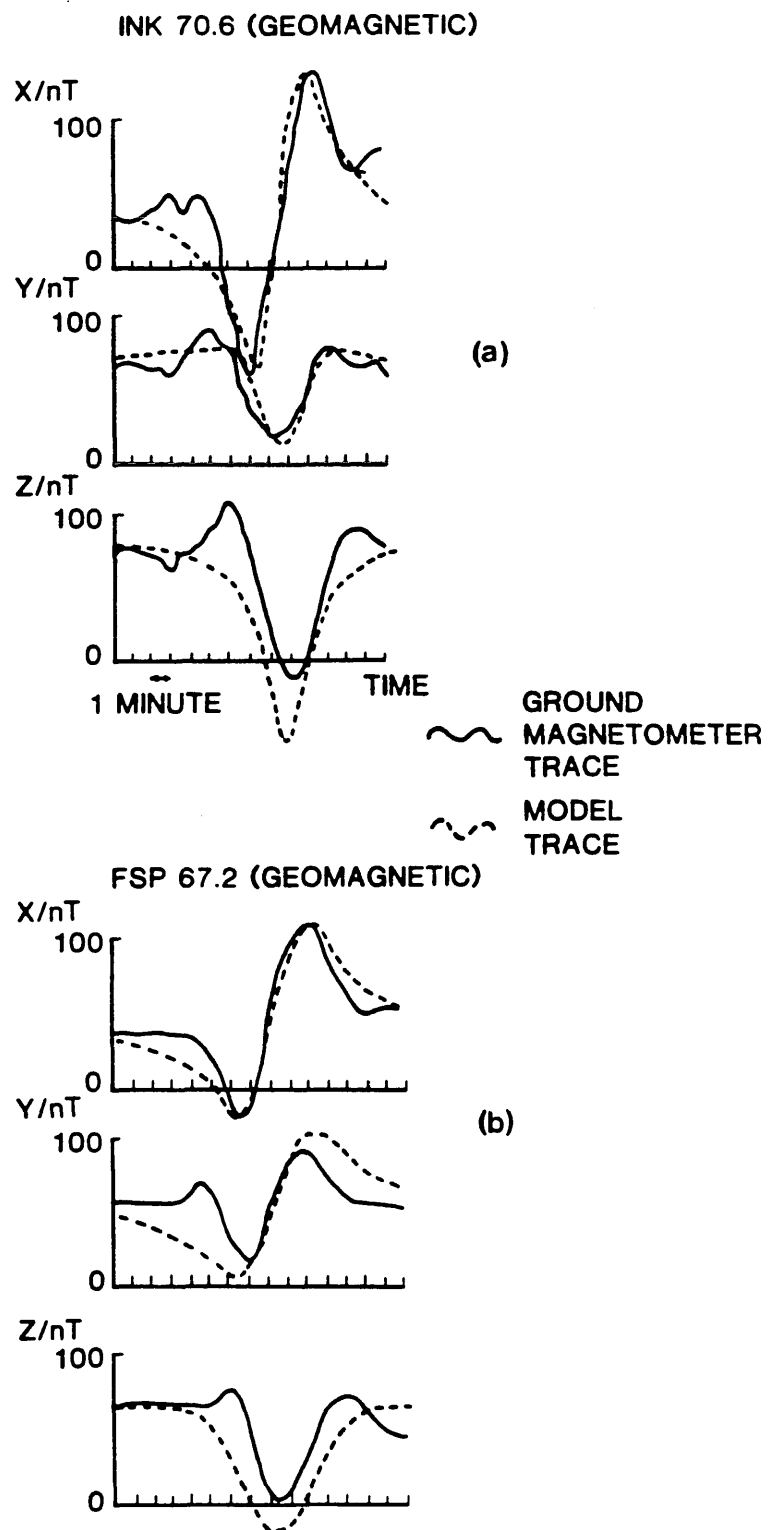


Fig. 3.8. Measured geomagnetic field components (solid line) at stations INK (Fig. 3.8a) and FSP (Fig. 3.8b). The dashed lines show predicted field perturbations from two FTE models, as explained in the text.

The B_x , B_y , B_z perturbations in the interval 01:00 - 01:15 U.T. at the stations INK (geomagnetic latitude 70.6° , 14:06-14:21 M.L.T.) and FSP (geomagnetic latitude 67.2° , 15:30-15:45 M.L.T.) are shown in Fig. 3.8a and 3.8b, respectively. We have compared them with the predicted ground magnetic perturbation from McHenry and Clauer's (1987) modelling of the ground signatures of FTEs, assuming a trajectory through the foot of a reconnected flux tube. One signature assumes a net upward and downward current of 5.8×10^5 A along the flanks of the flux tube (Southwood, 1985; 1987) whose foot is moving poleward at 2.3 km s^{-1} . We show this superposed (dashed lines) on the measured traces in Fig. 3.8a.

A second model postulates an axial current (Saunders et al., 1984; Lee, 1986) and predicts a different ground signature. For this case we consider a disturbance moving poleward and eastward over a station in the northern hemisphere at a speed of $\sim 400 \text{ m s}^{-1}$ carrying a current of 3.3×10^5 A. The resulting magnetic signature is superposed on the measured traces in Fig. 3.8b. The values of speeds and currents have been chosen to match the perturbation most closely (see McHenry and Clauer, 1987; and references therein). In both cases the modelled B_z variation have been scaled down from the theoretical value by a factor of 2. This is reasonable as the model takes no account of the finite conductivity of the Earth or nearby oceans (Lanzerotti et al., 1987). For magnetometers located near the sea (e.g. INK) induced currents can be very important (Boteler, 1978).

The observations and predictions match very well using these conditions. But we have traced the cause of the pulsations to be due to the change in the solar wind dynamic pressure. Thus changes in the solar wind ram pressure can create a travelling signature in the ionosphere very like the moving flux tube signatures postulated by Southwood (1987) for FTEs. Similar conclusions have been drawn by McHenry et al. (1988). There is thus the further important lesson that FTE signatures in the ionosphere can be mimicked by a variety of sources. We support the view of McHenry and Clauer (1987) that, for an unambiguous isolation of the low altitude FTE signatures, a close matrix of ground stations is important but would add that concurrent spacecraft data is essential.

3.4.4. *Global characteristics of the ground disturbance.*

Fig. 3.9 shows an expanded plot of the X-component of the magnetic field from 8 of the ground magnetometers. The oscillations at 01:40 U.T. are in fact seen on the ground at all but 3 of the 14 stations that we have available to us. The station array extends over an area on the ground ranging from 63° to 75.2° in latitude and 12:30 to 18:00 h in M.L.T., i.e. the whole of the high latitude afternoon ionosphere is encompassed. The interval plotted is now from 00:45 U.T. to 02:15 U.T. The box height corresponds to 100 nT but otherwise the format is the same as in Fig. 3.4. The top five panels show data from stations SAH,

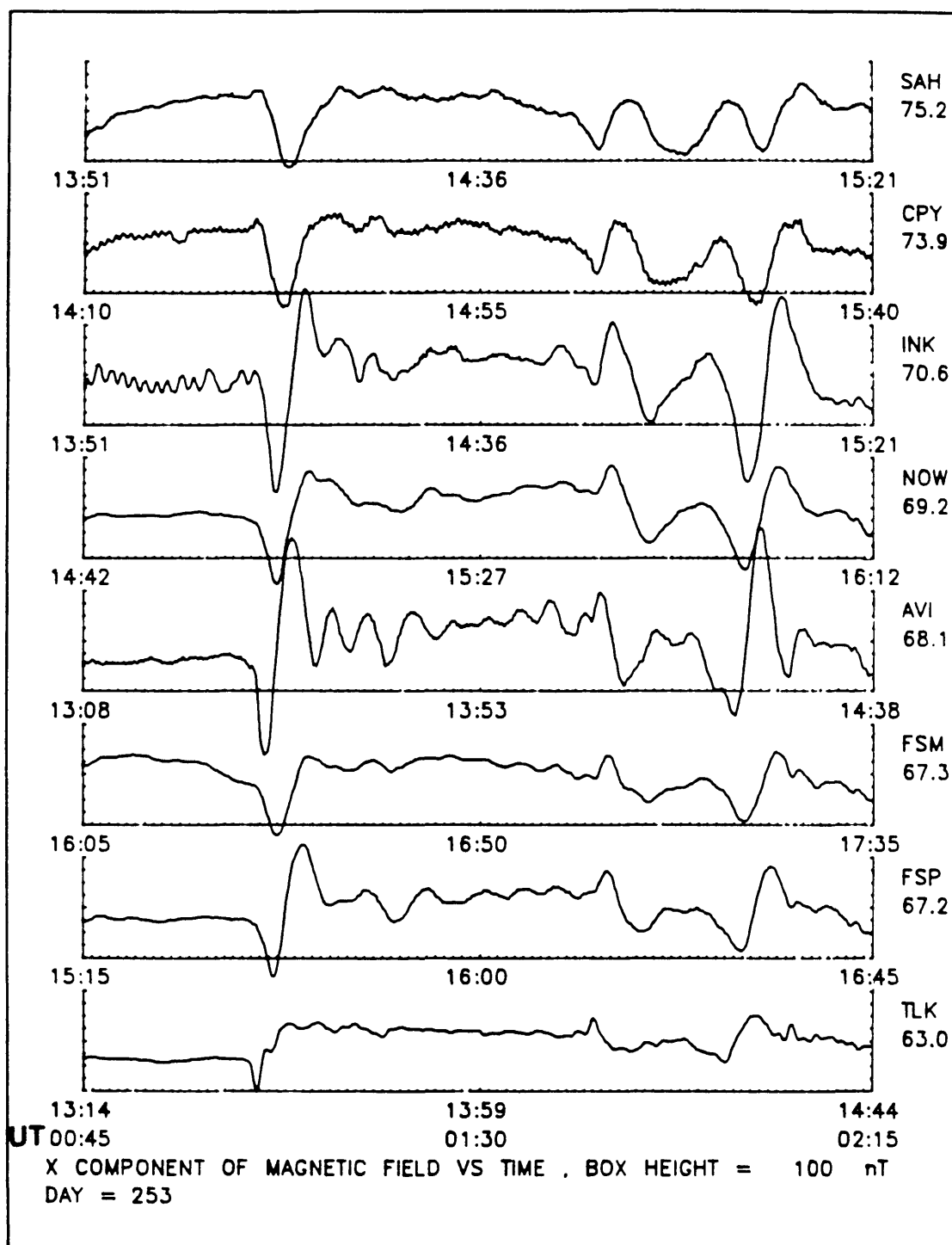


Fig. 3.9. X component of the geomagnetic field for the 8 ground stations shown in Fig. 3.4. The scales are expanded.

CPY, INK, NOW, AVI which are located at steadily decreasing latitudes but similar magnetic local times (within 1 h). Comparing the time of the first peak at each station for the ~01:00 U.T. oscillation there is a clear negative phase shift with increasing latitude. There is a similar phase shift with M.L.T. Comparing stations FSM and FSP (the sixth and seventh panels in the figure), which are just 0.1 of a degree of latitude apart, we see a negative phase shift with increasing local time. The same qualitative phase motion can be seen in the vertical component. The disturbance appears to propagate both northward and eastward on the ground corresponding to outward and tailward motion in the magnetosphere. The outward sense of direction is possibly attributable to the effect of field line resonance. Using stations SAH and INK (at the same M.L.T. and average 74.5° magnetic latitude, MLAT), we infer the poleward component of velocity at ~14:10 M.L.T. to be 4.3 km s^{-1} . The meridional velocity component, inferred from the data at stations FSM and FSP at 67.25° magnetic latitude and ~16:00 M.L.T. is 10.8 km s^{-1} .

3.5. Conclusions.

We have presented a study of magnetopause motion and associated ground magnetic field oscillations which appear to be caused by changes in the pressure of the solar wind. On the day in question the changes are caused in the main by changes (both increases and decreases) in the solar wind dynamic pressure and, in particular, by changes in the solar wind density. However, our interpretation of the magnetospheric signals, namely that they are simply the system response to varying pressure external to the magnetopause, means that similar effects would result from changes in solar wind magnetic field or gas pressure.

We have shown that changes in solar wind dynamic pressure can be large enough to give rise to boundary velocities of many tens of kms^{-1} and have directly confirmed the occurrence of such velocities.

Through most of the interval studied the IMF had a strong northward component. For long stretches of the data, the fields inside and outside the magnetosphere were close to parallel. Thus magnetic reconnection-related coupling at the magnetopause is unlikely a priori. Indeed, the only flux transfer event signatures observed in space were detected before 00:04 U.T. when B_z was of opposite sign.

We first considered the size of the lag to be expected between the detection of a pressure signature at the spacecraft in the solar wind and its arrival at the magnetopause and the detection of subsequent effects on the ground. The delay depends on the manner in which perturbations propagate both in the solar wind and in the terrestrial environment. We have made the particular assumption that the front in the solar wind is propagating radially from the Sun. Other inclinations of front are clearly possible and the delay at different points on

the globe could be changed in a major way if there were non-radial propagation. Similarly we have assumed that the disturbance in the magnetosheath and magnetosphere moves with the plasma in the sheath but propagates as a magnetohydrodynamic wave within the magnetosphere. More detailed calculations are needed but there is every reason to believe that the figure used for the delay between interplanetary space and the ground is of the correct order.

We used magnetic field data from a variety of stations to monitor the ground signals whilst two spacecraft were in the magnetopause vicinity. The pressure changes have also been associated with magnetic perturbations, both pulse-like signals and oscillations detected on the ground. During a very rapid compression localised oscillations were recorded on the ground. Long-lasting (about 4 cycles) signals were clearly detected at only two stations; elsewhere pulse like changes (one cycle or less) were recorded. If the signals are due to resonant field line excitation there may be some form of filter in the system that precludes magnetic shells at all latitudes being excited. Alternatively, it may be that some of the higher latitude stations such as INK, PEB, and CPY, do not see oscillations due to their being located at the feet of tubes which stretch into the polar cap and thus do not form a resonant cavity.

The pulse-like magnetic signatures could be modelled by the passage overhead of a dual current system like that proposed by Southwood (1987) for the ionospheric footprint of an flux transfer event. As we have already noted, there was no FTE activity recorded at the magnetopause at the time of these ground magnetic signatures. In addition the speed of motion of the disturbance pattern, 2.3 kms^{-1} , deduced for the Southwood pattern is very fast for actual material motion in the ionosphere (this is several times faster than the acoustic speed in the E region). Thus, unlike in the FTE model of Southwood where in the core of the disturbance there is a flux tube of plasma moving bodily through the surrounding medium, it seems likely that the speed observed is the speed of a front moving through the plasma in the ionosphere and there is not actual material motion at the high speed detected. It is important to note that McHenry et al. (1988) also report isolated travelling vortices in the ionosphere which travel at speeds well above the acoustic speed.

The speed deduced if the Saunders model is used is considerably slower (400 ms^{-1}). This could correspond to actual mass motion. The similarity of the models to the FTE signature predictions makes it very likely that there is localised field-aligned current flow in the perturbation.

In a second instance where oscillations were seen in the ground data the nett magnetopause motion was outward. We have obtained evidence from the spacecraft at the magnetopause that the boundary was moving at the same frequency as the signals detected on the ground

and that there were similar fluctuations in the solar wind dynamic pressure in the solar wind proper. In this latter case the oscillations detected on the ground were observed over a much larger range of latitude and longitude.

The success of the FTE model ionospheric signatures in describing observations which were certainly not due to FTEs is important. The high deduced speed of the signature may preclude there being any mass transport in the centre of the disturbance and so in this respect the model does not fit, but the study does highlight the need of great care in identifying potential signatures of impulsive reconnection at low altitude.

The presence of a tailward convecting signature in the ionosphere almost certainly indicates that the source solar wind pressure perturbation is producing some nett anti-solar flux transport in the magnetosphere and ionosphere. How large the transport is needs further study; as we have pointed out the motion detected need not be a material motion. Similarly, if the oscillations are due to waves in the magnetosphere or on the magnetopause propagating tailward, they also represent a nett tailward plasma transport (Southwood, 1979).

CHAPTER 4.

**THE CONTROL OF DAYSIDE IONOSPHERIC
CONVECTION AND MAGNETOSPHERIC
TOPOLOGY BY MAGNETIC RECONNECTION
BETWEEN THE IMF AND THE GEOMAGNETIC
FIELD. A CASE STUDY - SEPTEMBER 4, 1984.**

4.1. Introduction.

In this chapter we present concurrent data from disparate sources to elucidate the change in magnetospheric topology that occurs during the growth phase of a magnetospheric substorm.

The contention of Dungey (1961) that magnetic reconnection at the dayside magnetopause is the dominant process which drives the magnetospheric plasma circulation has been supported by numerous observations which demonstrate the predicted anti-correlation between the rate of plasma transport and the north-south component, B_z , of the interplanetary magnetic field (IMF) (e.g. Reiff et al., 1981; Etemadi et al., 1988).

Whilst the long term averaged behaviour of the magnetospheric system concurs with the steady state Dungey model, it has been recognised that at any instant the dayside and nightside reconnection rates are rarely balanced as they respond on different time scales to a change in the IMF B_z condition (e.g. Bargatze et al., 1985; Etemadi et al., 1988). This means that, whilst dayside reconnection is dominant, there is a nett increase in open magnetic flux which is eroded from the dayside magnetosphere and transported into the magnetotail; the so-called substorm growth phase (e.g. McPherron et al., 1973; see Fig. 4.1).

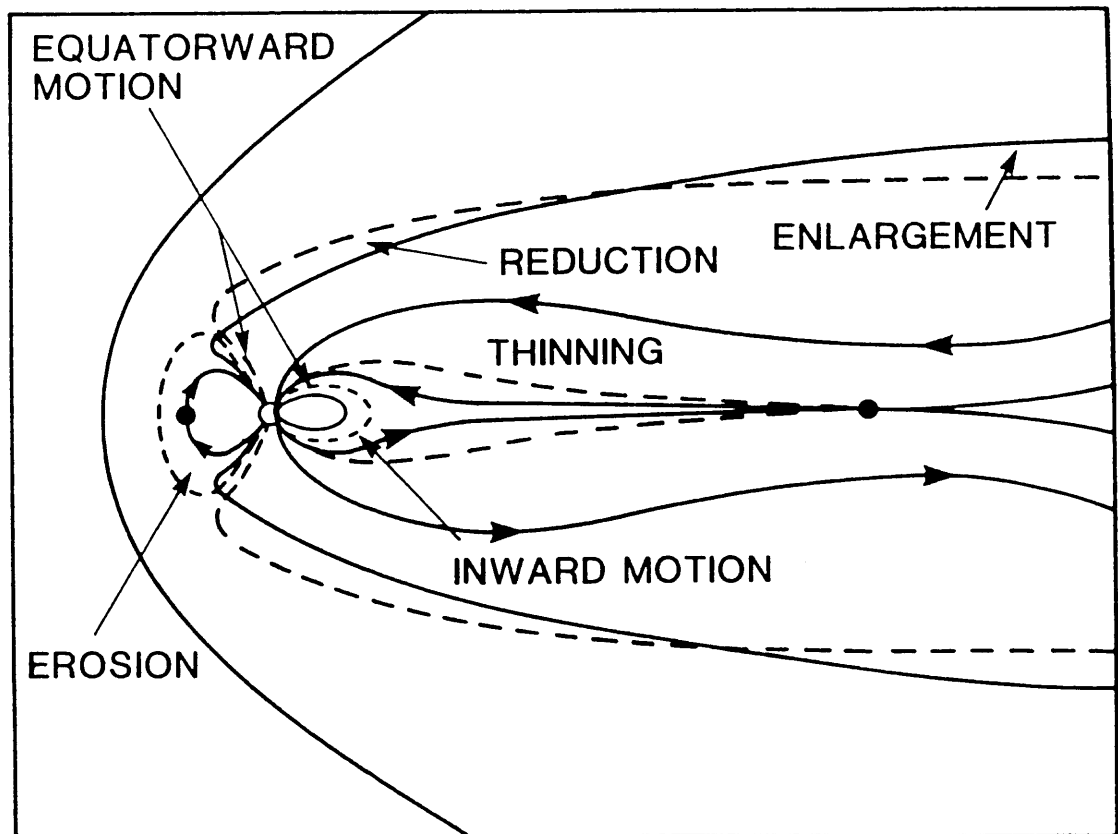


Fig. 4.1. An illustration of the major changes in magnetospheric topology during the substorm growth phase (after McPherron et al., 1973).

At ionospheric heights the incompressibility of the geomagnetic field means that the increase in open magnetic flux causes the polar cap area to grow. Assuming the polar cap to remain circular, erosion has the effect of displacing ionospheric plasma on closed magnetic field lines equatorward to accommodate the polar cap growth. The resultant time-dependent convection pattern was discussed in Chapter 2 (see Figs. 2.1 and 2.7).

In order to help the reader understand how the disparate data sets fit together, we shall summarise in advance the main features of the data that we present in the following sections and our interpretation of them.

On the afternoon of September 4, 1984 the IMF was compressed with a variable B_z component. Following ~ 1.5 hours of weakly negative or positive B_z , the IMF turned strongly southward at $\sim 13:40$ UT until $\sim 15:00$ UT (section 4.2.2. (i)). During this latter interval concurrent observations of the magnetopause and ionosphere demonstrate the magnetospheric topology to change due to an enhanced dayside reconnection rate.

In section 4.2.2. (ii) we present observations made by the AMPTE spacecraft which provide evidence of magnetic reconnection at the dayside magnetopause during the interval of southward IMF: flux transfer events were seen and accelerated plasma flows were recorded in an extended magnetopause boundary layer encounter which have been shown to satisfy the stress balance condition of reconnected field lines (Paschmann et al., 1986). In addition, we infer that the dayside magnetosphere was eroding with the magnetopause located well earthward of its expected position based upon the observed bow shock position and solar wind dynamic pressure. The prolonged boundary layer encounter is interpreted as further evidence of erosion with the magnetopause moving earthwards with the spacecraft.

Ground magnetometers from the late afternoon local time sector recorded large (~ 500 nT) magnetic bays (see section 4.2.3. (iii)) showing the development of strong ionospheric currents in association with the enhanced plasma flows recorded by E region radars (sections 4.2.3. (ii) and (iv)). The dayside auroral zone flow strength increased almost immediately after the arrival of the southward turning of the IMF at the dayside magnetopause. The high latitude east-west flow reversal, expected to demarcate the polar cap boundary (see Chapter 1), was observed to move equatorward between $\sim 14:00$ UT and $\sim 15:00$ UT with a concomitant equatorward component to the flow. This is consistent with an expansion of the polar cap due to the prevailing magnetospheric erosion. Ancillary data were studied to determine the polar cap boundary motion based upon particle precipitation characteristics (sections 4.2.2. (iii) and 4.2.3. (i)). In section 4.3 we show that both particle and field data were consistent with an expansion of a geomagnetically offset circular polar cap over the interval of southward IMF. The increase in polar cap area is in agreement with the es-

estimated erosion of the dayside magnetosphere. During this interval it is argued that dayside reconnection was dominant over that in the tail.

After ~ 1 hour the polar cap expansion was arrested and reversed: at ~ 15:00 UT the polar cap rapidly contracted coincident with a northward turning of the IMF and a peak in the nightside auroral zone flow strength, as measured by the AL index (not shown). It is thought that nightside reconnection was now dominant due to an earlier enhancement in its rate initiated by the magnetic flux build-up in the tail and a reduction in the dayside reconnection rate due to the northward turning of the IMF.

4.2. Data Overview and Analysis.

The data we shall examine in this study come from a wide range of observing sites and instruments in space and on the ground. By a detailed analysis of these concurrent data sets we are able to learn much about the time dependent behaviour of the magnetosphere-ionosphere system and the control exerted upon it by the IMF. The period of interest extends from 12:00 - 18:00 UT on September 4, 1984. However, we shall concentrate in particular on the central 2-3 hours of this interval.

At ionospheric heights we shall see four distinct phases. Initially the convection strength was weak, peaking at typical auroral zone latitudes (~ 70° GM latitude). After ~ 13:50 UT the convection strength increased substantially and the auroral electrojet migrated equatorward over ~ 1.25 h interval. Thus at a fixed ground station we shall observe a changing overhead convection, accompanied by a changing ionosphere, as the topology of the magnetosphere changed. After ~ 15:00 UT the auroral convection peak moved rapidly poleward and at a given station we will consequently observe in reverse the temporal sequence of events in the preceding phase. By 15:40 UT the situation was again like that in the initial phase prior to the convection enhancement at ~ 13:50 UT. Flows slowly subsided in this final phase.

The north-south component of the IMF can be divided into similar phases and it will be our aim to relate the ground observations to each other and to the spacecraft observations in the solar wind and at the dayside magnetopause.

4.2.1. State of the magnetosphere.

The geomagnetic field was moderately- to highly-disturbed on September 4, 1984 ($\Sigma K_p = 36+$) with peak disturbance occurring in the afternoon (3-hour averages, 12-18 UT, $K_p = 7, 8-$).

When $K_p = 8$ Chubb and Hicks (1970) predict the most equatorward auroral arc to be located at an invariant latitude of (65.7 ± 2.5) degrees near midday and (60.2 ± 2.5) degrees near midnight, based on an extrapolation of their results.

A large magnetic storm began on this day with a storm sudden commencement at $\sim 07:45$ UT. The AE and AL indices exhibit three prominent enhancements of ~ 1 -2 hour duration with maxima at $\sim 08:10$ UT (AE ~ 1200 nT), $\sim 10:40$ UT (AE ~ 1100 nT), and $\sim 14:55$ UT (AE ~ 1900 nT). It is on the latter substorm sequence that we shall concentrate our attention.

Until $\sim 14:00$ UT the ring current was fairly quiet ($D_{ST} > -20$ nT). Between 13:00 UT and 15:00 UT the hourly average value of D_{ST} decreased rapidly from $D_{ST} = -8$ nT to $D_{ST} = -32$ nT. In the following hour the ring current reached its peak value for the day with $D_{ST} = -58$ nT before gradually declining.

4.2.2. Spacecraft data.

On September 4, 1984 data were available from four spacecraft. Extra-magnetosphere observations were made by ISEE 2, AMPTE-UKS and -IRM. Fig. 4.2 shows the trajectories of ISEE 2 and the AMPTE spacecraft pair (separated by only ~ 50 km) in GSM coordinates over the interval 12:00 - 16:00 UT.

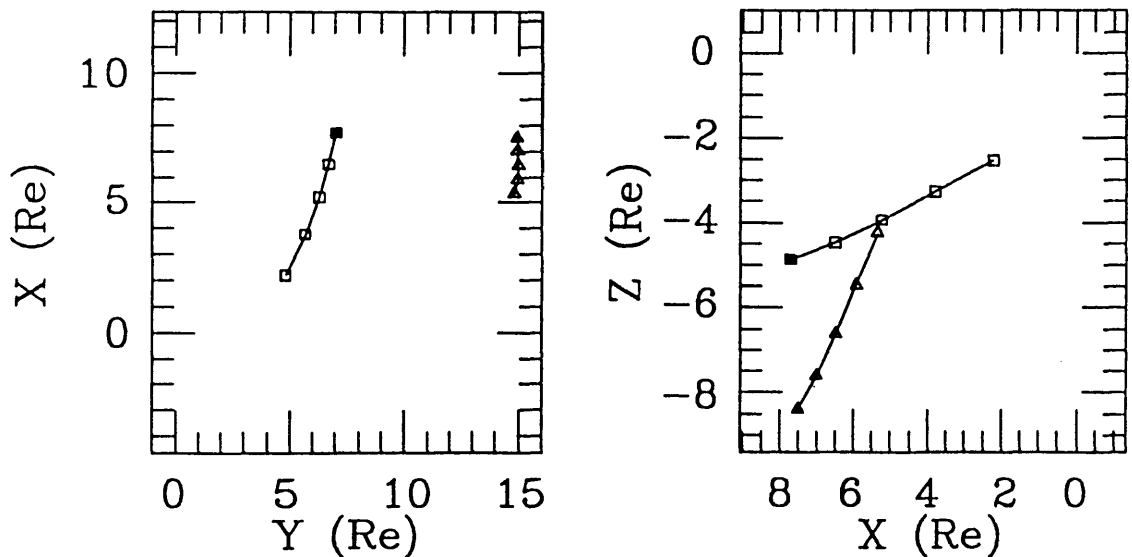


Fig. 4.2. Spacecraft trajectories on September 4, 1984. ISEE 2 (triangles) and AMPTE (squares) spacecraft positions are shown in GSM coordinates at hourly intervals from 12:00 UT (shaded symbol).

4.2.2. (i) IMF observations.

Fig. 4.3 presents magnetic field data in GSM coordinates from the ISEE 2 spacecraft for the period 12:00 - 15:10 UT. Plasma data were not available from this satellite. In the bottom panel is shown the field magnitude. This remained fairly constant over the interval, except for a sudden decrease at 15:01 UT, a few minutes before the cessation of data coverage. The observed field was that of the solar wind, significantly compressed ($B \sim 25$ nT) over normal levels ($B \sim 5$ nT; see Chapter 1). A rapid shock-like field compression (not shown) from ~ 6 nT to ~ 11 nT was observed by ISEE 2 at $\sim 06:35$ UT, remaining steady at this value at least until a data gap at $\sim 07:35$ UT. When data coverage resumed at 12:13 UT the field strength had increased further to the value of 22 nT seen in the figure. The field decrease at 15:01 UT may therefore have been a reverse shock at the trailing edge of a compressed IMF sector.

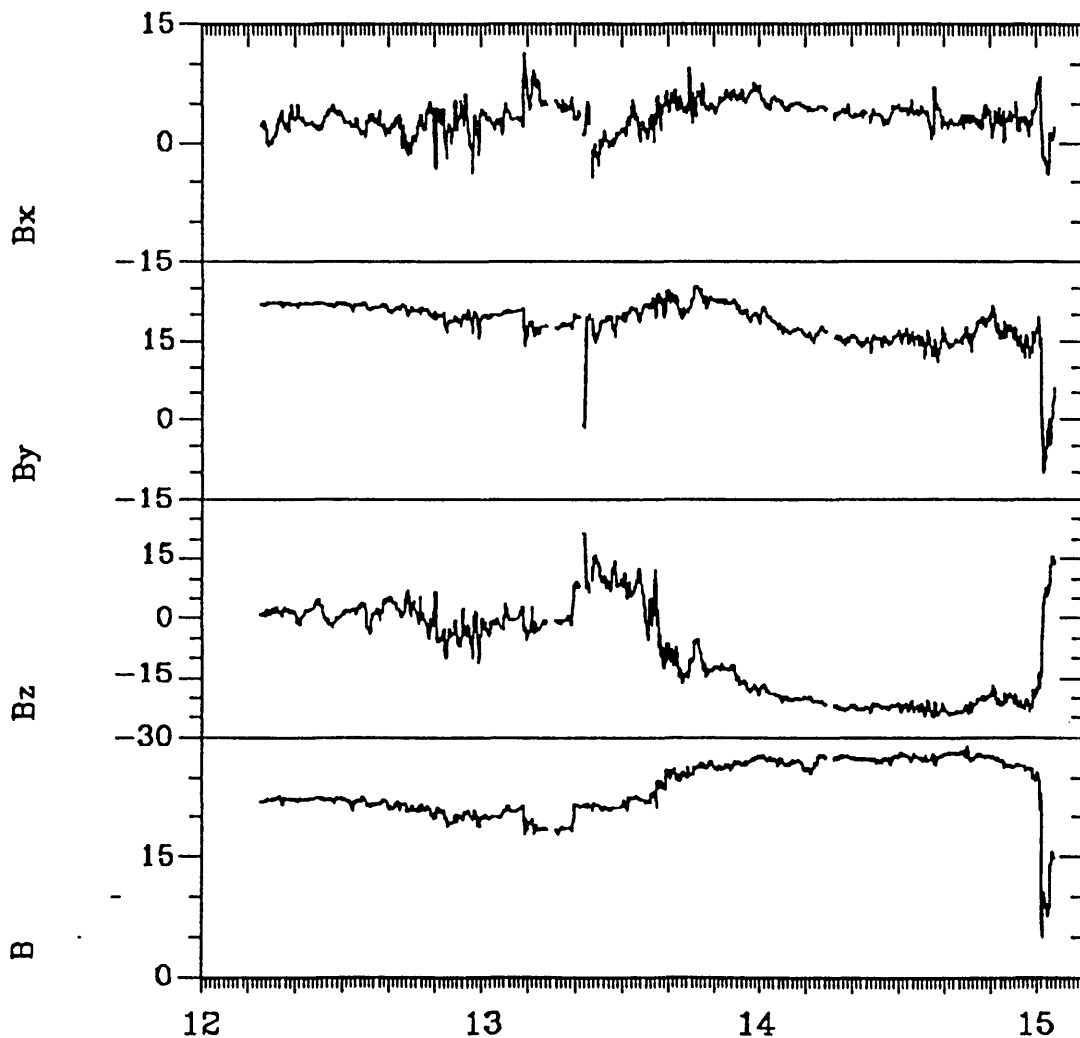


Fig. 4.3. ISEE 2 observations of the IMF in the interval 12:00 - 15:10 UT, September 4, 1984. Panels show, from top to bottom, B_x , B_y , B_z GSM components and total magnitude, B , of the IMF, in nano-Tesla (nT).

From 12:13 UT to 15:00 UT the IMF lay almost in the Y-Z (GSM) plane with a continuously strong, positive B_y component. However, the polarity of the B_z component varied over this interval. Initially, until 13:19 UT, B_z was small and variable in polarity. In the subsequent 15 min it was strongly northward, before turning strongly southward by 13:38 UT. B_z then remained large and negative until 15:00 UT when it increased sharply, coincident with the shock-like field decrease. Simultaneously, IMF B_y decreased.

4.2.2. (ii) Magnetopause observations.

Fig. 4.4a shows magnetic field data in GSM coordinates from the AMPTE-UKS spacecraft between 13:00 UT and 14:50 UT. Initially the satellite observed the same, ~ 20 nT, solar wind field strength (bottom panel) as at ISEE 2. As it moved earthward in the mid-afternoon local time sector UKS encountered the Earth's bow shock at 13:19 UT at a radial distance, $R = 10.0 R_E$, inside the typical position of the magnetopause (Fairfield, 1971). Coincidentally, the sudden increase in B_z detected by ISEE 2 in the solar wind arrived at UKS. At this time the two spacecraft were at almost the same distance upstream of the Earth, but well separated in the plane perpendicular to the Sun-Earth line. Thus the simultaneity of signal reception points to the IMF disturbance front being orthogonal to the Sun-Earth line and hence to the expected direction of the solar wind.

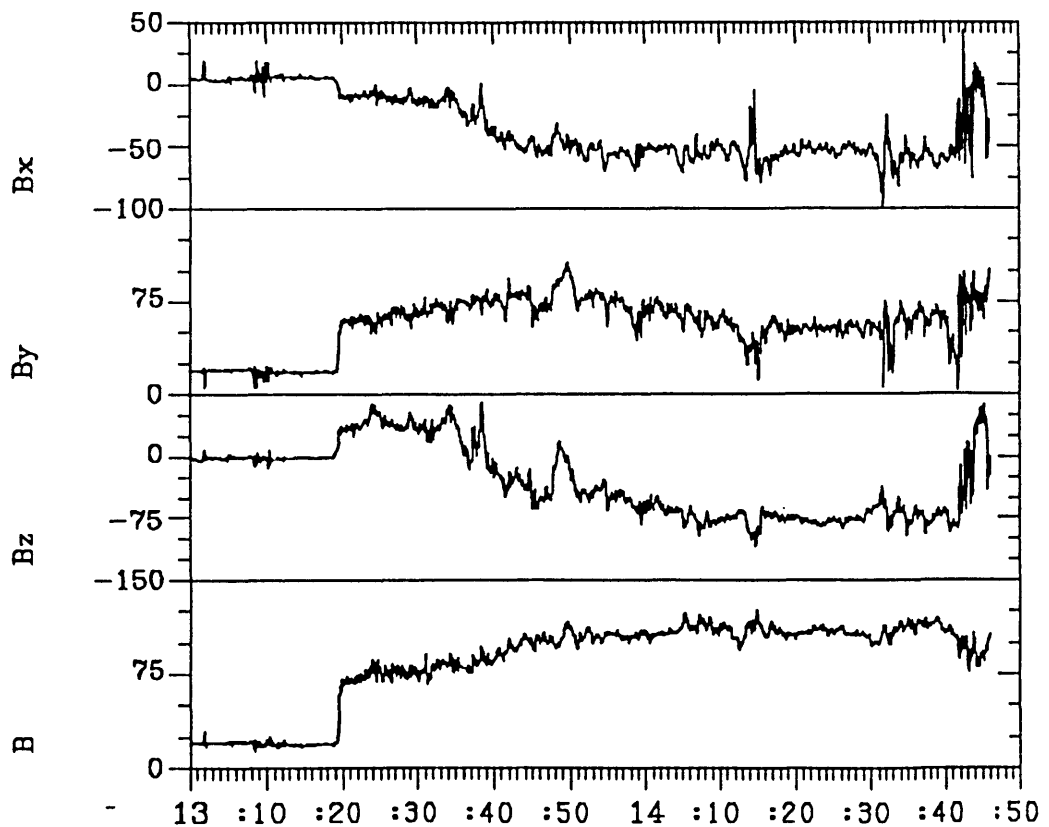


Fig. 4.4a. AMPTE-UKS measurements in the interval 13:00 - 14:50 UT, September 4, 1984. Panels show, from top to bottom, B_x , B_y , B_z GSM components and total magnitude, B , of the magnetic field, in nT.

As UKS traversed the outer magnetosheath (13:20 - 14:10 UT), variations in the B_z component on time scales of > 1 min had clear counterparts in the IMF recorded concurrently at ISEE 2 e.g. the increase in B_z centred on 13:46 UT at ISEE 2 and seen by UKS at 13:48 UT. A cross-correlation analysis (Freeman and Southwood, 1988b) has shown that the increasing lag with UT between these low frequency variations is consistent with them having propagated at the local plasma convection speed with an upstream phase front which was contained in the plane perpendicular to the Sun-Earth line.

In the inner magnetosheath the cross-correlation begins to break down as signatures are seen in the UKS data which have no counterpart in the solar wind observations. Two such events, centred on 14:14 UT and 14:31 UT, have been identified (Southwood et al., 1986) as flux transfer events (Russell and Elphic, 1978) by their bipolar variation in the field component normal to the magnetopause and associated high-speed flows. At 14:42 UT UKS encountered the magnetopause, just prior to the cessation of scientific observations at 14:46 UT. The magnetopause was located at only 8.1 R_E .

After the UKS instruments were switched off, the AMPTE-IRM, separated from UKS by only ~ 54 km, continued operation for at least another 30 min. The data collected in this period has been found to be most interesting and has been analysed by Paschmann et al. (1986) to show evidence of quasi-steady reconnection.

Fig. 4.4b shows AMPTE-IRM plasma and magnetic field data between 13:10 UT and 15:10 UT. The IRM and UKS spacecraft encountered the magnetopause simultaneously at 14:42 UT. However, the magnetosphere proper was not entered by the IRM until 15:06 UT. For 19 min (14:42 - 15:01 UT) the IRM spacecraft remained in the magnetopause boundary layer region of mixed magnetosheath and magnetospheric plasma, except for a brief exit into the magnetosheath at 14:51 UT. It then re-exited into the magnetosheath for 5 min at 15:01 UT, before the final magnetopause crossing at 15:06 UT.

In the boundary layer region accelerated plasma flows can be seen. Paschmann et al. (1986) applied quantitative energy and momentum balance tests to the observations and were thus able to identify the high speed flows as being consistent with the acceleration caused by the Maxwell stresses of reconnected field lines.

During the boundary layer encounter the spacecraft moved $\sim 0.5 R_E$ earthward. Later in this paper we shall show that the inward motion of the magnetopause during this period cannot be accounted for by any change in solar wind dynamic pressure, but that it is the ongoing reconnection that is causing the earthward magnetopause migration. We shall further show that the magnetospheric erosion seen at the IRM spacecraft is consistent with data from low altitude sites.

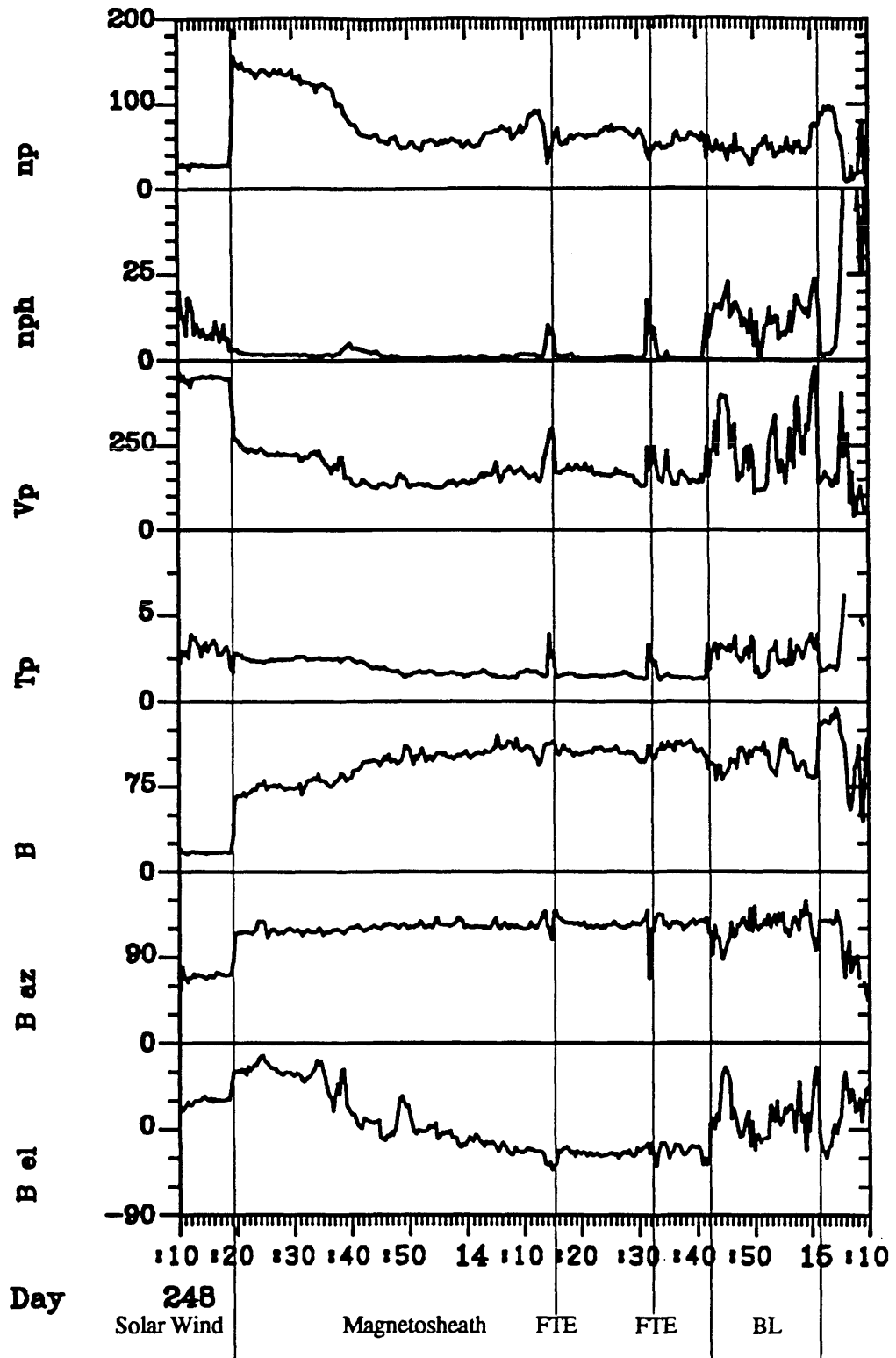


Fig. 4.4b. AMPTE-IRM magnetosheath crossing in the mid-afternoon local time sector on September 4, 1984 showing flux transfer event (FTE) observations and an extended boundary layer (BL) encounter, both with the presence of high-speed flows. Panels show from top to bottom: proton number density, n_p (cm^{-3}); partial number density, n_{p9} ($*100 \text{ cm}^{-3}$), of protons with energies above 9 keV; proton bulk speed, V_p (km s^{-1}); proton temperature, T_p ($*10^6 \text{ }^\circ\text{K}$); magnetic field strength, B (nT); azimuthal and elevation angles of GSM magnetic field ($B_{az} = 90^\circ$ is eastward, $B_{el} = -90^\circ$ is southward).

4.2.2. (iii) *Low altitude particle data.*

The Defence Meteorological Satellite Program spacecraft, DMSP-F7, was a low-altitude (840 km), polar-orbiting satellite. Onboard electron and ion spectrometers were capable of measuring precipitating particle fluxes in the energy range 30 eV - 30 keV for both electrons and ions (Hardy et al., 1984). The orbit was Sun-synchronous with a period of ~ 100 min. Thus the spacecraft would typically cross the auroral oval four times within this period, at a range of magnetic local times.

Fig. 4.5a-c show the electron and ion data from three high-latitude passes, each sampling some portion of both the dayside and nightside auroral oval. The format for each figure is the same. The middle and bottom panels are colour spectrograms, for electrons and ions respectively, showing the particle flux at each energy in the instrument energy range versus time. The particle energy is indicated on the abscissa and the universal time, spacecraft magnetic local time and geomagnetic latitude are shown on the ordinate. The colour scale for particle flux is given to the right of the figure.

12:12 - 12:32 UT pass: Referring to the time axis on Fig. 4.5a, DMSP moved over the southern polar cap in this period from a late evening MLT to a late morning MLT. At the beginning of the data interval, 12:12 - 12:15 UT, high fluxes of ions and electrons can be seen, demarcating the nightside auroral oval. There was little evidence of discrete activity within this region and the fluxes were typical of a fairly quiet nightside oval. At 12:15 UT the poleward edge of the precipitation region was located at -67.8° MLAT at 21:46 MLT.

As the spacecraft traversed towards the dayside very little precipitation was seen until the high ion and electron fluxes of the dayside cusp were encountered at 12:25 UT. The high fluxes lasted for just over a minute, corresponding to a latitudinal band, -77.0° MLAT to -72.5° MLAT, at $\sim 10:50$ MLT. The equatorward edge of the cusp is thought to have been at -75.2° MLAT (12:25 UT) with a boundary layer region at lower latitudes in which there was several keV electron precipitation. The thick cusp and boundary layer, together with the high energy dayside electrons are all thought to be characteristic of a northward IMF (Newell and Meng, 1987). The IMF recorded by ISEE 2 up to 10 min prior to the cusp observation had a north-south component in the range, $-1 \text{ nT} < B_z < 4 \text{ nT}$ (see Fig. 4.3).

14:46 - 15:06 UT pass: In Fig. 4.5b a narrow, isolated cusp signature can be seen at 14:47 UT. The equatorward edge was located at 66.8° MLAT at 09:17 MLT, much more equatorward than in the earlier pass. The high electron fluxes extended poleward to 68.0° MLAT, whilst the low energy ions precipitated yet further poleward. The fountain-like appearance of the ion spectrogram shows that lower energy cusp ions precipitated poleward of higher energy cusp ions. This velocity filter effect indicates strong poleward

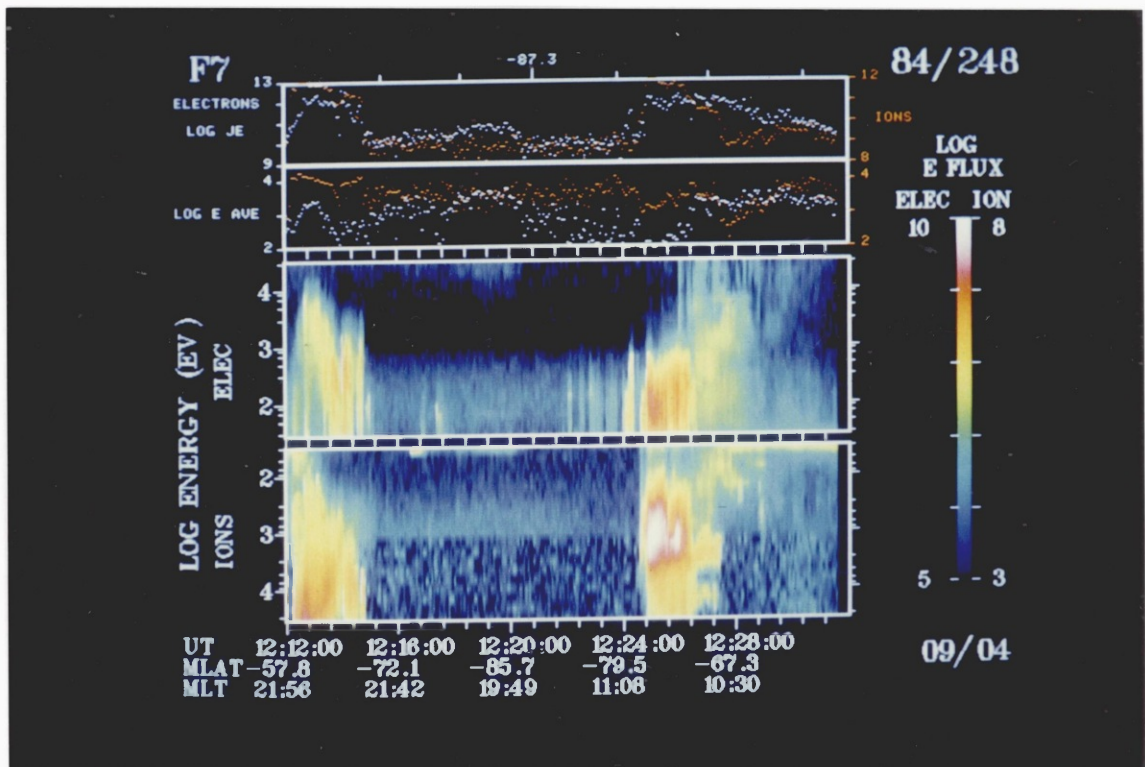


Fig. 4.5a. DMSP-F7 precipitating particle data in the interval 12:12 - 12:32 UT.

The DMSP particle instrument apertures have a width $< 8^\circ$ and point towards local zenith so that at high latitudes all particles observed are within the loss cone. The top and second panels show electron and ion energy flux ($\text{eV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$) and average energy (eV), respectively. The third and bottom panels show respectively electron and ion spectrograms of differential energy flux ($\text{eV cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{eV}^{-1}$). The colour scale is to the right of the figure. The measurements are versus Universal Time (UT). The magnetic latitude (MLAT) and magnetic local time (MLT) of the spacecraft are also shown at the base of the figure.

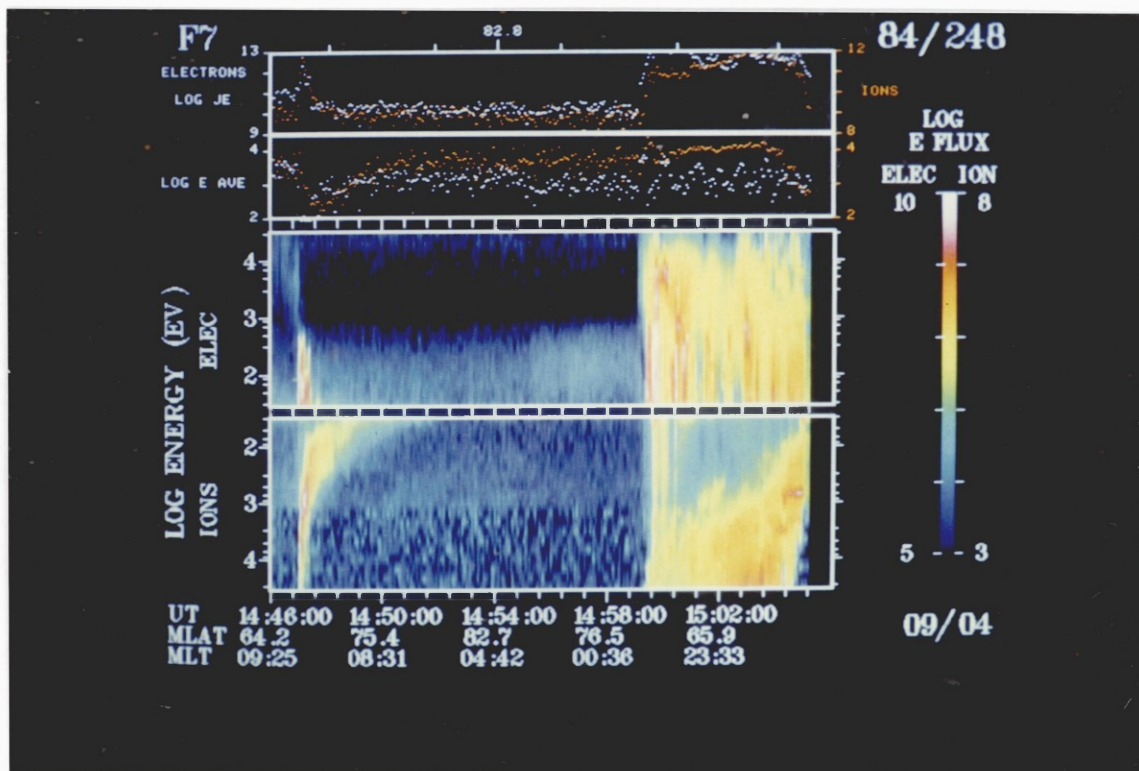


Fig. 4.5b. DMSP-F7 precipitating particle data in the interval 14:46 - 15:06 UT. See Fig. 4.5a for details.

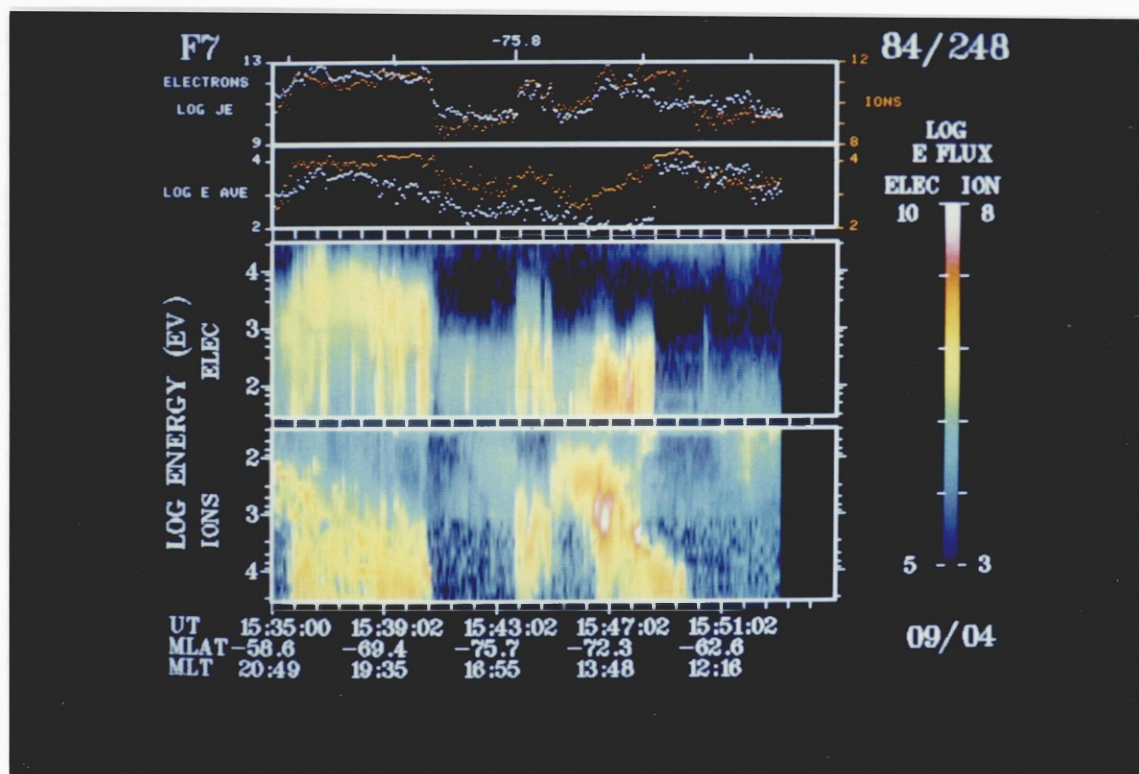


Fig. 4.5c. DMSP-F7 precipitating particle data in the interval 15:35 - 15:55 UT. See Fig. 4.5a for details.

convection in the cusp region (Reiff et al., 1977). The observations are typical of a southward IMF, as observed at this time by ISEE 2. Finally, the observation of the cusp at such an early local time is unusual and may be dependent on IMF B_y (Newell et al., 1989), though the strongly positive B_y orientation prevailing during this mid-morning cusp crossing is contrary to expectations.

After the polar cap traversal the spacecraft encountered the high fluxes of the nightside oval from 14:59 UT onwards. The poleward edge was located at 72.8° MLAT at 00:14 MLT and the flux of ~ 10 keV electrons peaked just equatorward of this, decreasing as the satellite moves to lower latitude. The nightside oval was very thick ($\sim 15^\circ$ MLAT) and discrete activity was evident throughout it. In summary, the nightside magnetosphere was much more active than in the earlier crossing.

15:35 - 15:55 UT pass: Initially the spacecraft passed through the southern hemisphere auroral oval, 0.5-2.5 h behind the dusk meridian. As can be seen in Fig. 4.5c, high particle fluxes were observed between -58.6° MLAT at 20:49 MLT (15:35 UT) and -71.9° MLAT at 18:31 MLT (15:41 UT). The oval was still fairly thick with some discrete activity, but particle fluxes were lower than those observed about 30 min earlier in the northern hemisphere.

The spacecraft then moved around the afternoon side of the Earth on a trajectory more closely parallel, than orthogonal, to a line of geomagnetic latitude. Two distinct periods of high particle fluxes were observed in the intervals 15:44 to 15:45 UT (-75.1° to -74.0° MLAT; 16:21 to 15:22 MLT) and 15:46 to $\sim 15:49$ UT (-74.0° to $\sim -68^\circ$ MLAT; 14:30 to $\sim 12:54$ MLT). The former comprised much weaker fluxes than the latter and may have been late afternoon boundary layer plasma. A cusp-like signature was evident in the second period whose equatorward edge was located at -72.2° MLAT, 13:47 MLT (15:47 UT). However, the signature was not as clear as in the previous pass. Boundary layer plasma at lower latitudes and a discrete auroral emission near -71° MLAT, together with the higher cusp latitude, suggest that IMF B_z was likely to be northward again at this time.

In summary, the three DMSP passes tell us that the dayside cusp migrated $\sim 8.4^\circ$ MLAT equatorward between 12:25 UT and 14:47 UT, before returning $\sim 5.4^\circ$ MLAT poleward by 15:47 UT. At about 15:00 UT, shortly after the most equatorward cusp observation, the nightside auroral oval was very broad and active, with particle energies and fluxes significantly above those in the earlier and later nightside passes. We note that the almost noon-midnight MLT pass centred on $\sim 12:20$ UT revealed the particle signature of the nightside polar cap boundary to be at a geomagnetic latitude equatorward of that on the dayside. As discussed in Chapter 2, this indicates that the centre of the generally circular polar cap was displaced anti-sunward of the geomagnetic pole by several degrees.

4.2.3. Ground data.

A variety of ground-based instruments, designed to probe the ionosphere, were operational on September 4, 1984. Table 4.1 lists the ground stations contributing to this study, their location, and the instruments used at each site.

Table 4.1 - Ground observing stations.

Station	Geomagnetic Latitude ($^{\circ}$ N)	Geomagnetic Longitude ($^{\circ}$ E)	Instrumentation
Bear Island	71.1	124.5	Magnetometer.
Tromso	67.1	116.7	Magnetometer.
Kilpisjarvi	66.3	117.3	Magnetometer.
Kiruna	65.3	115.6	Magnetometer.
Nurmijarvi	57.9	112.6	Magnetometer.
SABRE	64.0 - 68.4	96.4 - 107.5	140 MHz bistatic radar.
Barrow	68.5	241.1	Magnetometer.
College	64.6	256.5	Magnetometer.
Syowa	-69.7	77.7	Magnetometer, riometer, ionosonde, 50 MHz radar.
Halley Bay	-65.8	24.3	Magnetometer, ionosonde.

4.2.3. (i) Riometer and ionosonde data.

Information on the ionospheric plasma concentration can be extracted from riometer and ionosonde measurements. Data is available to us from two southern hemisphere stations, Halley Bay (-65.8° geomagnetic (GM) latitude) and Syowa (-69.7° GM latitude). At 15:00 UT the former is located at $\sim 11:50$ MLT and the latter at $\sim 15:30$ MLT.

The lower trace in Fig. 4.6 shows the variation in cosmic noise over the second half of September 4, 1984, as recorded by the Syowa riometer. The instrument measures the 30 MHz VHF radiation from the region of the cosmos directly overhead at Syowa which has a smooth diurnal variation shown by the dashed line in the figure. However, on shorter time scales, enhancements in D region ionisation can attenuate the cosmic signal measured at the station on the Earth's surface. Such an effect can be seen for several hours around

15:00 LT. In this way the instrument can be used to detect periods of enhanced D-region ionisation which would normally arise from energetic (> 20 keV) particle precipitation from the magnetosphere.

The upper trace in Fig. 4.6 shows the north-south (H) component of the geomagnetic field measured at Syowa. Over precisely the period of the negative bay in the magnetogram, $\sim 14:25 - 15:25$ UT ($17:25 - 18:25$ LT), the riometer trace was close to the background level; whilst before and after this interval the signal attenuation was large. We deduce that from $\sim 10:10$ UT ($\sim 13:10$ LT) to $\sim 16:10$ UT ($19:10$ LT) there was significant energetic particle precipitation into the D region ionosphere, except between $\sim 14:25$ UT ($17:25$ LT) and $15:25$ UT ($18:25$ LT) when precipitation was absent or very small.

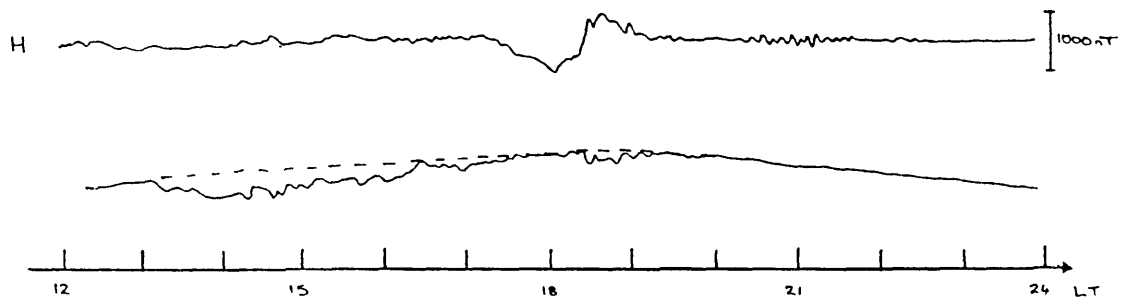
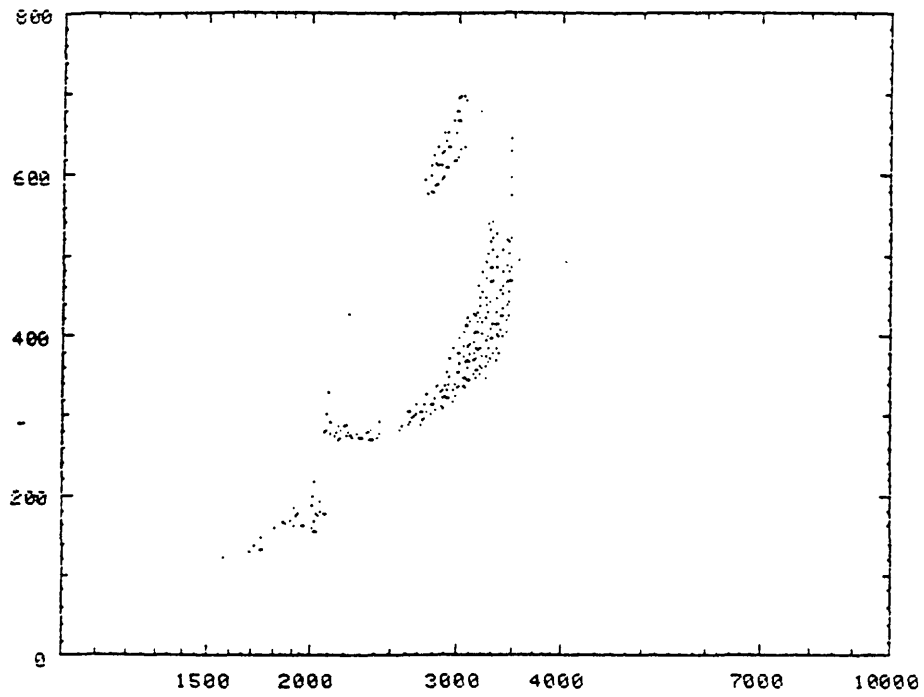


Fig. 4.6. Riometer measurements of 30 MHz cosmic noise over Syowa station, Antarctica; 12:00 - 24:00 LT (09:00 - 21:00 UT), September 4, 1984.

Knowledge of the E and F region electron concentration can be found from ionospheric sounder data. A description of the instrument used at Halley Bay was given by Dudeney et al. (1983). The instrument transmits vertically propagating radio waves at a range of frequencies. The waves reflect from an ionospheric layer where the local plasma frequency matches the wave frequency. The increase in electron density with height up to the F region peak means that as the wave frequency increases so does the reflection height. When the wave frequency exceeds the maximum plasma frequency at the F region peak the radio waves propagate into space. Fig. 4.7 shows two ionograms with signal propagation distance along the abscissa and signal frequency as the ordinate. For a vertical incidence geometry the plot qualitatively shows the ionospheric electron density height profile.

Fig. 4.7a shows a Halley Bay ionogram taken at 14:00 UT (12:00 LT, 10:50 MLT). The sounder observed a normal mid-latitude ionosphere. The E layer was a little spread, indicating the presence of some irregularities in electron concentration, and had a maximum plasma frequency of 2.1 MHz ($\sim 5 \times 10^{10}$ electrons m^{-3}). The F layer was also a little spread with a maximum plasma frequency of 3.6 MHz ($\sim 1.5 \times 10^{11}$ electrons m^{-3}). A

(a)



(b)

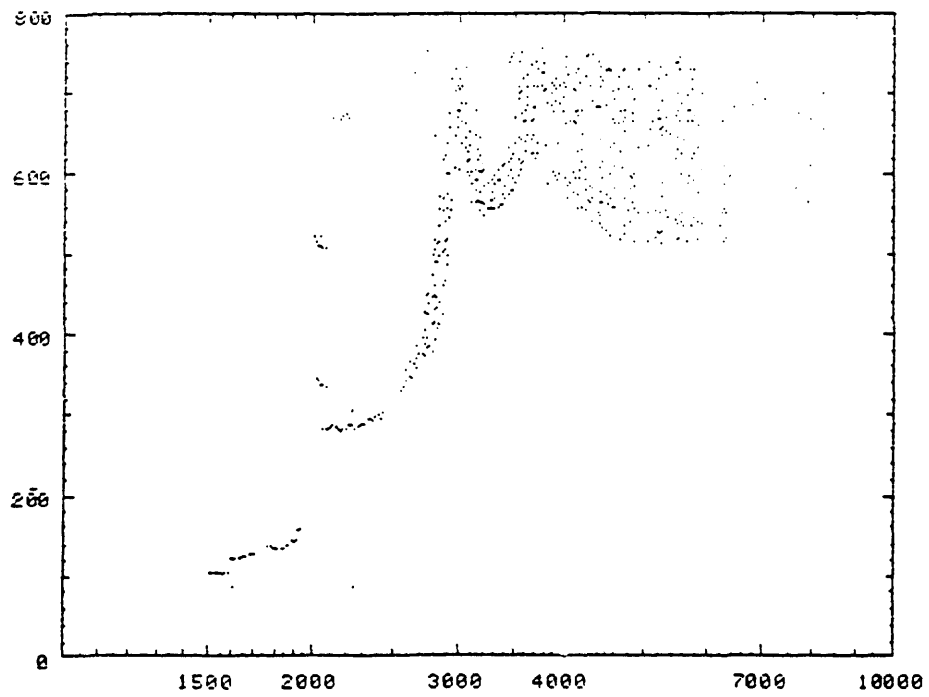


Fig. 4.7. Ionospheric sounder data from Halley Bay at (a) 14:00 UT, and (b) 15:00 UT, on September 4, 1984. The ordinate is virtual reflection height (km) and the abscissa is sounder frequency (kHz).

secondary reflection packet was present at 600-700 km. The values and shape of the F layer were typical of local noon conditions at this time of year and solar activity.

Three subsequent ionograms (not shown) taken at 15 min resolution between 14:15 UT and 14:45 UT showed the ionosphere above Halley Bay to remain unchanged, except for small variations due to the changing solar zenith angle.

At 15:00 UT (13:00 LT, 11:50 MLT) the ionogram showed some extra features (Fig. 4.7b). There was a normal E and F layer over the station, but there were also weak echoes at a distance of 520 - 760 km away with a maximum plasma frequency in excess of 8 MHz ($\sim 7 \times 10^{11}$ electrons m^{-3}). These corresponded to a "new" F layer $\sim 4^\circ$ polewards of the Halley Bay station. The 5-fold increase in the electron concentration indicates that this was the signature of the cusp or cleft (Rodger and Broom, 1986). It was most likely to be the cusp since Halley Bay was at 11:50 MLT at the time of the observation.

Fortuitously, the operational cycle of the Halley Bay instrument meant that extra measurements were taken at 1 min resolution over the period 15:01 - 15:14 UT, but only at selected frequencies. At 15:01 UT the situation was largely unchanged, though the distance to the reflecting region appears to have increased by ~ 50 km, indicating a poleward motion. From 15:02 UT to 15:14 UT sounding was on only 6 frequencies. Echoes from the cusp region were lost at 15:10 UT due to increased ionospheric absorption. The effect of absorption was first detected on the oblique path to the cusp layer. One minute later absorption was detected in the overhead ionosphere. If the reflecting cusp structure was 600 km away at a height of 300 km and absorption was taking place at 80 km altitude, then the equatorward phase speed of the absorption region was 2.3 km s^{-1} .

The full ionogram at 15:15 UT showed a greatly increased minimum frequency for echoes ($f_{\min} = 3.1 \text{ MHz}$), indicating that the absorption region was moving over the station. From 15:30 UT to 16:15 UT radio wave blackout was observed. At 16:30 UT a dense F layer was present, but with some absorption still present ($f_{\min} = 2.7 \text{ MHz}$). The F layer was found to have maximum plasma frequencies of $\sim 6.8 \text{ MHz}$ and $\sim 9.0 \text{ MHz}$, 75 km equatorward and 50 km poleward of the station respectively. This is consistent with the equatorward edge of the polar cleft. The ionogram at 16:45 UT was in blackout, but a denser cleft layer was seen over Halley Bay at 17:00 UT. The maximum electron concentration of the cleft layer subsequently diminished to a near-normal level by 17:45 UT.

In summary the Halley Bay ionospheric sounder observations tell us that by 15:00 UT the polar cusp near noon MLT had migrated equatorward to a latitude of $\sim -70^\circ$ GM latitude. In the next minute it was observed to move poleward at up to 900 m s^{-1} . Over the next two hours a dense F layer, typical of the equatorward edge of the polar cleft, was present over

the station. From time to time, this F layer was obscured by radio wave absorption caused by energetic particle precipitation. After 17:00 UT the cleft probably moved further poleward as the ionosphere above Halley Bay returned to a more usual mid-latitude state.

In the interval 13:00-16:45 UT ionospheric soundings at 15 min resolution were taken at Syowa station. Fig. 4.8 shows selected ionograms from this period. The ionograms are in essentially the same format as those recorded at Halley Bay (Fig. 4.7).

From 13:00 - 13:15 UT Syowa was in blackout due to D-region absorption caused by energetic particle precipitation.

At 13:30 UT (Fig. 4.8a) there was quite a thick E layer with some irregularities and a high maximum plasma frequency (though a low minimum plasma frequency). The F layer had a high maximum plasma frequency of ~ 8 MHz, an enhancement of ~ 4 over typical undisturbed values. Consequently particle precipitation was still strong at this time, but not of high enough energy to cause D region absorption.

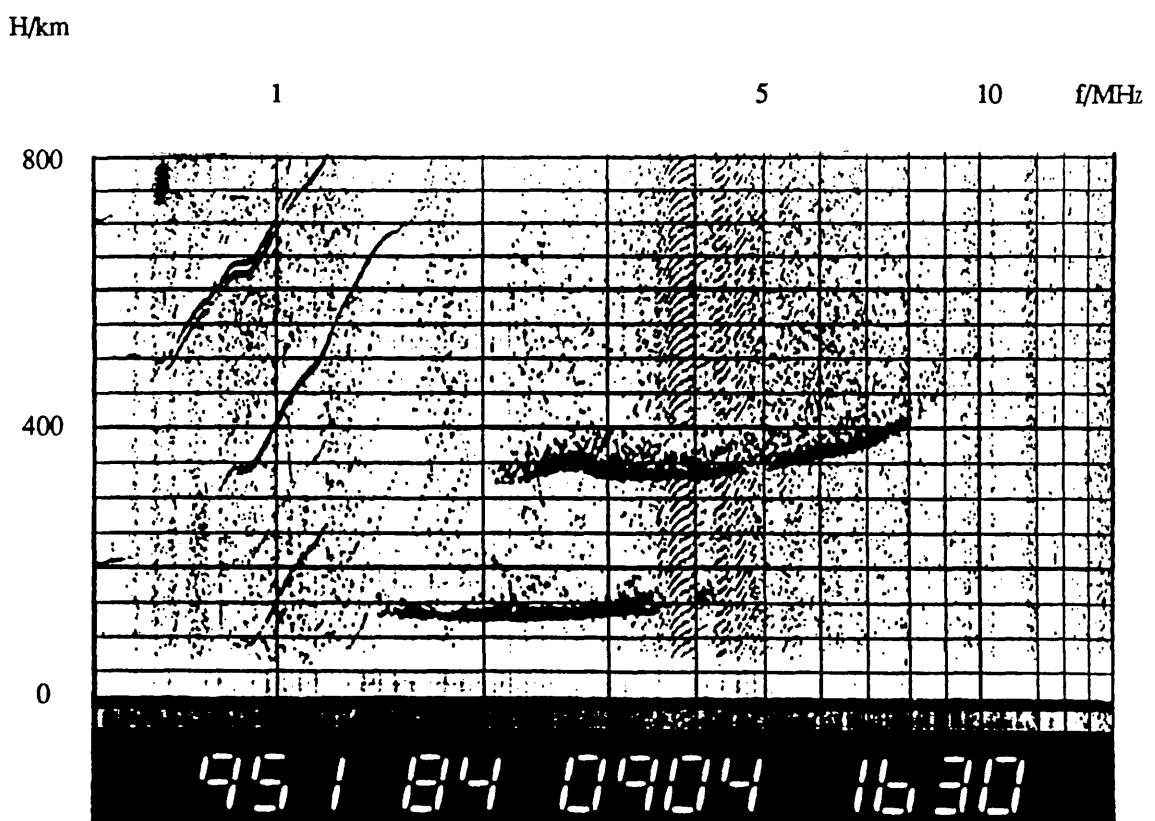
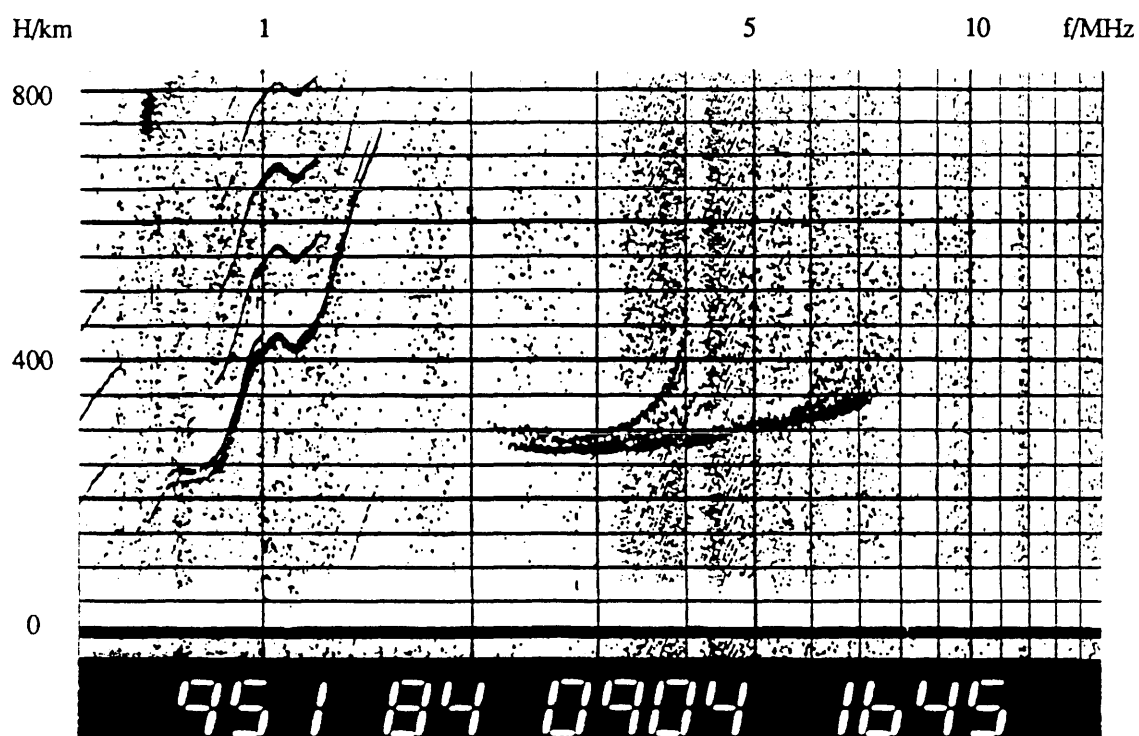


Fig. 4.8a. Ionospheric sounder data from Syowa at 13:30 UT on September 4, 1984. The ordinate is virtual reflection height, H (km), and the abscissa is sounder frequency, f (MHz).

(b)



(c)

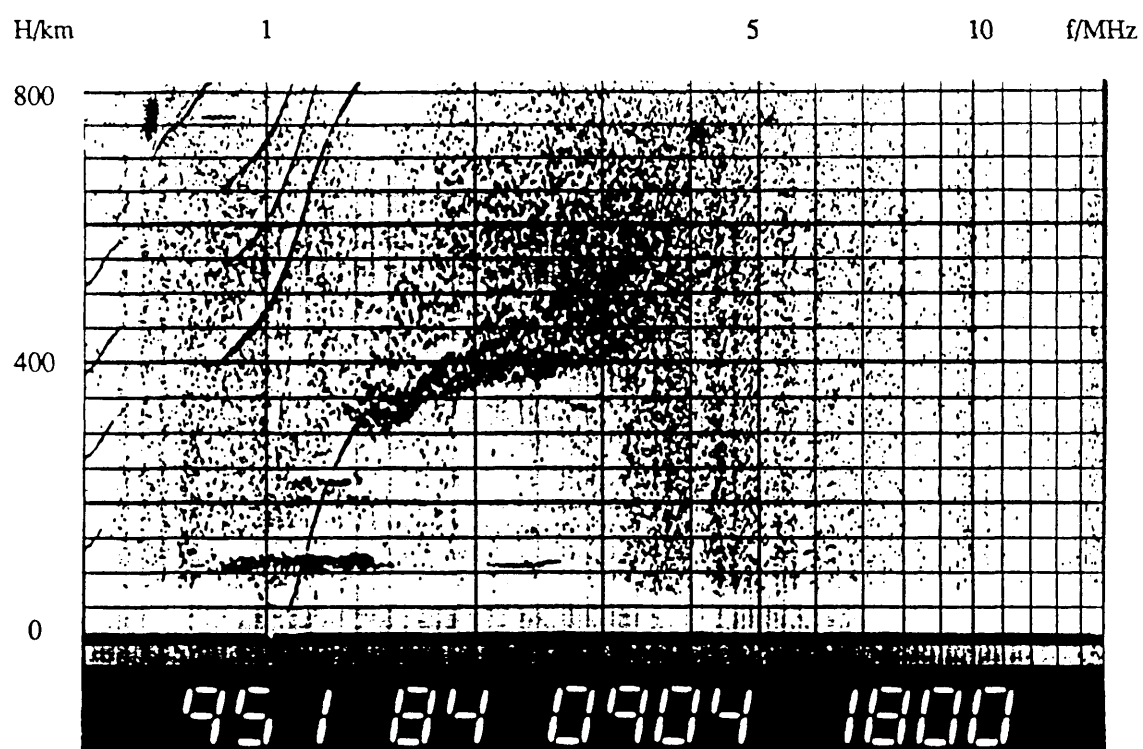


Fig. 4.8. Ionospheric sounder data from Syowa at (b) 13:45 UT, and (c) 15:00 UT, on September 4, 1984. The ordinate is virtual reflection height, H (km), and the abscissa is sounder frequency, f (MHz).

At 13:45 UT (Fig. 4.8b) there was no E layer recorded and the minimum plasma frequency had increased to above 2 MHz in the F layer. A high density F layer, maximum plasma frequency ~ 8 MHz, was observed, as at 13:30 UT. However, there was also an additional undisturbed F layer trace, maximum plasma frequency ~ 4 MHz.

At 14:00 UT and 14:15 UT a thick E layer of high plasma concentration obscured observation of the F layer. This implied that the maximum plasma frequency in the F region was below the E region maximum of 3.5 MHz. The E layer height was 100-150 km, consistent with electron precipitation in the energy range 1-5 keV and characteristic of the afternoon oval.

From 14:30 UT to 15:15 UT the E layer weakened, revealing a very spread F layer of low maximum plasma concentration. At this time the station must have moved into a region of very weak precipitation such as the polar cap. The ionogram recorded at 15:00 UT is shown in Fig. 4.8c as an example.

The next two ionograms at 15:30 UT and 15:45 UT recorded blackout. The associated high energetic particle fluxes occurred at a time when the station was in a region of expected minimum precipitation (18:30 - 18:45 LT).

From 16:00 - 16:45 UT the ionosphere was in a state similar to that at 14:00 - 14:15 UT, which was interpreted as being the auroral oval. The maximum plasma frequency of the F layer was below 4 MHz as very little F layer was seen.

In summary, the ionospheric sounding data at Syowa showed evidence of a disturbed magnetosphere. Throughout most of the interval 13:00 - 16:45 UT the ionograms were characterised by high plasma concentrations at low ionospheric heights (D and E regions) caused by strong energetic particle fluxes. These energy fluxes are only seen in the closed field line region of the magnetosphere and probably originated from particle energisation due to reconnection in the magnetotail. However, an exception to this behaviour occurred at Syowa for 45 min in the interval 14:30 - 15:15 UT. During this time weak precipitation, typical of the polar cap, was recorded. This accords with the observation of little or no attenuation of the cosmic noise measured by the Syowa riometer. We conclude therefore that the polar cap boundary in the mid-afternoon MLT sector passed equatorward over Syowa (-69.7° GM latitude) near 14:30 UT, returning poleward between 15:15 UT and 15:30 UT. This interpretation is consistent with the brief observation of the polar cusp near noon MLT at a similar GM latitude by the Halley Bay station at 15:00 UT, as we shall discuss later.

4.2.3. (ii) Syowa radar data.

An auroral Doppler radar experiment was operational on September 4, 1984, at Syowa station (Igarashi et al., 1982). The experiment comprised two antenna beams, one directed toward geomagnetic South and the other at 32.8° W of this (toward geographic South). Measurements are taken of the backscattered signal from 3 m irregularities generated by the gradient drift and two-stream instabilities in the E region ionosphere. The Doppler shift of the backscattered signal yields the irregularity drift speed along the antenna line of sight. When the flow is uniform between and across the two ionospheric volumes probed by the radar beams the line of sight velocities can be geometrically combined to estimate the $\mathbf{E} \times \mathbf{B}$ electron drift velocity in this region.

Fig. 4.9 presents the Syowa Doppler radar data over the period 12:00 - 18:00 UT. In the top and fourth panels are shown the backscatter Doppler spectra at ~ 52 s resolution along the antennae directed toward the geomagnetic pole and the geographic pole respectively. The ranges of the two reflection cells are different such that they lie at different geomagnetic longitudes, but at the same geomagnetic latitude (-72.3° GM latitude). The latter is 2.6° poleward of Syowa station itself. In the second and bottom panels of the figure are shown the r.m.s. line of sight speeds and relative backscatter powers from the geomagnetically and geographically directed antennae respectively. The former measurement is shown by a dot and the latter by a vertical line. Finally, in the centre panel is presented the east-west (H) component of the geomagnetic field recorded at Syowa station.

From 12:00 UT to 13:50 UT the radar recorded sporadic ionospheric flows. At $\sim 13:50$ UT the backscatter power increased in both antennae as the flows increased. The backscatter power continued to remain strong in one or both antennae until $\sim 16:20$ UT. This period of strong flows can be sub-divided into three distinct regimes.

In the intervals 14:05 - 14:30 UT and 15:30 - 15:50 UT the Doppler spectrum was generally broad with backscattered power at a range of Doppler shifts. This probably indicates that much small scale structure, i.e. less than the range cell size (~ 15 km), was present in the region of the ionosphere probed by the radar. In the E region, patchy conductivity can be caused in the auroral oval by energetic particle precipitation from the magnetosphere. In the periods when small scale structure in the E region was observed by the radar, ionospheric sounder and riometer data showed that strong precipitation was indeed occurring into the E region, with particles penetrating even into the D region.

In between these two periods the character of the backscatter spectrum changed. From 14:30 UT to 15:30 UT the backscattered power was much more localised about a single Doppler shift, as might be expected for steady flow in a uniform plasma. During this time

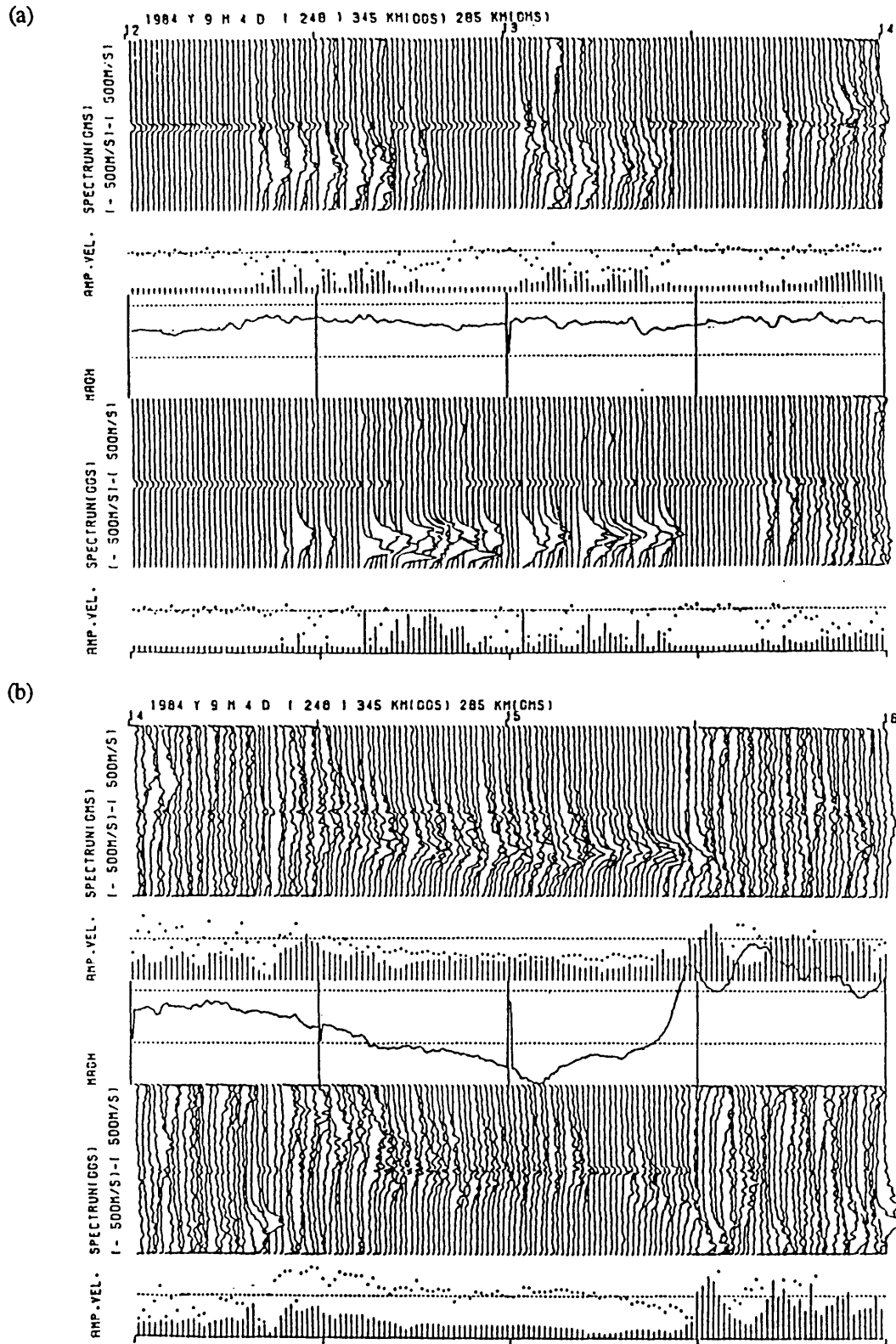


Fig. 4.9. Syowa radar data over the intervals, (a) 12:00 - 14:00 UT, and (b) 14:00 UT - 16:00 UT, on September 4, 1984. The top panel shows the backscatter Doppler spectrum measured along a beam pointing towards geomagnetic south. The second panel shows the relative backscatter amplitude (vertical bars) and r.m.s. Doppler velocity (dots) derived from the spectrum. The lower two panels show the same measurements, but for a beam pointing towards geographic south. The centre panel shows the H component of the magnetic field measured at Syowa station.

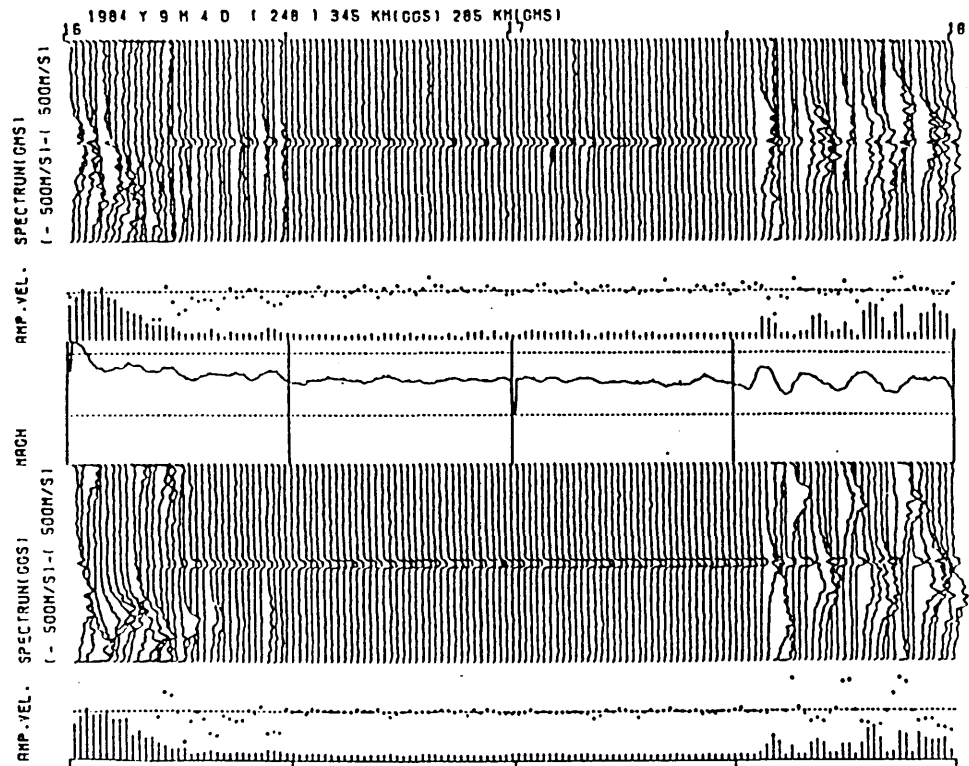


Fig. 4.9c. Syowa radar data over the interval 16:00 - 18:00 UT on September 4, 1984.

ionospheric sounder and riometer data from Syowa station gave evidence of only weak precipitation into the ionosphere which was attributed to the station having entered the polar cap.

The observation of a more spatially uniform ionosphere between 14:30 UT and 15:30 UT means that the geometrical addition of the line of sight speeds is likely to yield a good approximation to the $\mathbf{E} \times \mathbf{B}$ electron drift velocity at this time. The flow direction can be seen to change systematically over the interval. Initially, at $\sim 14:30$ UT, it was directed toward Syowa station primarily along the geographically directed antenna beam. The other beam registered a near zero Doppler shift implying the flow was orthogonal to it. Thus we conclude that at this time the flow direction was purely eastward in the geomagnetic frame. Near 15:00 UT the flow was approximately orthogonal to the geographically directed beam and was directed away from the station in the geomagnetically directed beam. Hence the flow had rotated by this time to $20^\circ - 30^\circ$ poleward of eastward in the geomagnetic frame. The magnitude of the flow was about 500 ms^{-1} . At the end of the interval, near 15:30 UT, the flow had almost equal components along both beams away from the station. Thus the flow at this time was $\sim 15^\circ$ west of poleward in the geomagnetic frame.

The observation at $\sim 15:00$ UT of a strong steady eastward component to the Southern hemisphere mid-afternoon ionospheric flow shows the radar to have been probing a region inside the polar cap with a convection system being driven under a large positive IMF B_y . The detection of polar cap flows concurs with the ionospheric sounder (Fig. 4.8c) and riometer (Fig. 4.6) data at this time. The inference of a strong duskward component to the IMF is in agreement with the ISEE 2 observations (Fig. 4.3), taking communication times into account. By examining the r.m.s. line of sight velocities we find that the east-west component of the vector flow reversed polarity from westward to eastward at 14:21 UT, and from eastward to westward at 15:29 UT. These convection reversals are expected to correspond to the polar cap boundary.

In summary, we interpret the radar data as showing the polar cap boundary to have moved equatorward over the radar viewing area at $\sim 14:20$ UT to a location equatorward of it. Subsequently it moved poleward back over the radar at $\sim 15:30$ UT to a position probably only slightly poleward of it at $\sim 16:00$ UT.

Finally, it is informative to compare the H component of the geomagnetic field measured at Syowa station (centre panel, Fig. 4.9) with the radar observations. As we shall discuss in more detail later, large (> 10 nT) perturbations in the high latitude geomagnetic field are generally attributable to Hall currents in the E region ionosphere generated by the plasma convection driven by the solar wind - magnetosphere interaction. In the simplest approximation the northward field perturbation is proportional to the westward component of the $\mathbf{E} \times \mathbf{B}$ drift velocity. In the hour interval centred on 17:00 UT when both radar beams detected little ionospheric motion near Syowa, we can see that the H component of the geomagnetic field was very steady. If we consider this level to be the unperturbed value of the north-south field component, then we can infer a polarity and relative magnitude of the overhead east-west plasma flows from the field perturbations about this level. For example, in the interval 14:25 - 15:26 UT the H component had a large negative perturbation corresponding to a strong eastward component to the overhead ionospheric flow. This is almost exactly as observed by the radar. The reason for the qualification is that the negative bay in the H component was nested within the period when eastward flow was observed by the radar. However, this observation is in agreement with, and further supports, our view that the polar cap boundary moved equatorward and then poleward over Syowa station at this time. If Hall currents from directly overhead contribute to the major proportion of the magnetic perturbation then, when the polar cap boundary moved equatorward, the eastward polar cap flows would have been seen first by the radar which viewed the ionosphere poleward of Syowa station where the magnetometer was sited. Similarly when the polar cap boundary retracted poleward the radar would have returned into the auroral

oval later than the station. From the measured lags we can estimate the polar cap expansion and contraction speeds at Syowa to have been of order 1 km s^{-1} .

However, as we shall see later, current distributions which are asymmetrical about the east-west flow reversal can alter the apparent position of the polar cap boundary, and hence any estimate of the boundary speed. It can be inferred from the radar and magnetometer data that such an asymmetry did exist near Syowa. Around 14:20 UT the average auroral oval flows were weaker than those inside the polar cap (though the radar measured considerable scatter in the auroral zone flow speed). This has the effect of moving the H component reversal equatorward of the polar cap boundary, and hence leads to an overestimate of the polar cap expansion speed. However, we note that the observed nesting of the magnetometer reversals within the radar reversals means that the offset of the H component reversal from the flow reversal was less than the inter-station separation i.e. $< 290 \text{ km}$. The latitudinal asymmetry in the east-west flow component is further evidence of an effect on the ionospheric convection pattern from the prevailing positive IMF B_y component. Later, when the polar cap contracted, the radar and magnetometer data from Syowa suggest that the auroral oval and polar cap flow speeds were more comparable.

Lastly, when the polar cap boundary is inferred to have been at its most equatorward location at $\sim 15:00 \text{ UT}$, both the radar and the magnetometer observed polar cap flows. If we assume these flows to have been uniform over the length scale separating the two viewing areas, then an estimate of the polar cap conductivity at this time can be made. The measured flow speed at the radar is $\sim 400 \text{ ms}^{-1}$, which caused a magnetic deflection of $\sim 300 \text{ nT}$ on the ground. The height integrated Hall conductivity, in the absence of ground induction effects, is thus estimated to have been $(19 \pm 4) \text{ mho}$ (see section 4.2.3. (iii)), which is $\sim 40\%$ larger than an empirically estimated Hall conductivity during disturbed times and appropriate to a location at 70° GM latitude in the mid-afternoon ionosphere at equinox (Wallis and Budzinski, 1981).

4.2.3. (iii) *Scandinavian magnetometer data.*

Data from five ground magnetometers sited in Norway, Sweden and Finland have been examined for the period of interest on September 4, 1984. As can be seen from Table 4.1, the stations are at a similar magnetic local time ($\sim \text{UT} + 3 \text{ h}$), but spaced over a wide latitudinal range ($57.9^\circ - 71.1^\circ \text{ GM}$ latitude). The central station in the latitudinal chain is Kilpisjarvi which is located at a lower magnetic latitude (66.3° GM latitude) and later magnetic local time ($\sim 2.6 \text{ h}$) in the northern hemisphere than Syowa in the South.

It is instructive to compare and contrast the magnetograms from these two stations and interpret them in terms of the ionospheric Hall current that produced the magnetic perturbations (see below). Fig. 4.10 presents the measured geomagnetic field in Cartesian coordinates between 12:00 UT and 18:00 UT. Negative bays of similar magnitude (~ 250 nT) in the Z component of the field were registered at both stations between $\sim 14:00$ UT and $\sim 16:00$ UT. In both cases the negative sense implies a decrease in the ambient field and is thus consistent with both stations having been located under, or near to, a poleward gradient in the eastward flow component. In the afternoon hours, such a gradient is only likely to exist at the poleward edge of the auroral oval near the polar cap boundary where the westward auroral zone flows reverse to eastward in the polar cap. In the centre and equatorward region of the auroral zone we would expect a poleward gradient in the westward flow as the convection electric field weakens at lower latitudes (see Chapter 2). This would result in a positive bay in the Z component of the geomagnetic field. The lowest latitude station in this chain, Nurmijarvi, did indeed record such behaviour (not shown).

Also common to both stations was the negative bay in the H component which developed up to 40 min prior to 15:00 UT. We argued above that at Syowa this interval corresponded to an entry into the eastward flow region of the polar cap. It appears therefore that a similar expansion of the polar cap was observed in the northern hemisphere. The observation of a negative perturbation in the Z field component which peaked close to the reversal between positive and negative bays provides additional evidence to support this view. During the polar cap expansion phase both stations recorded an equatorward component to the flow (a negative/positive perturbation in D in the northern/southern hemisphere). Just after 15:00 UT the inferred flow turned poleward at Syowa corresponding to the polar cap contraction phase. Interestingly, only a brief, weak positive excursion in D was observed at Kilpisjarvi during this period.

Although the stations recorded generally similar behaviour, important differences are also apparent between the two magnetograms. Firstly, around 14:00 UT both stations were inferred to be in the auroral zone region, but the magnitude of the (positive) H perturbation differed greatly, from ~ 50 nT in the southern hemisphere to ~ 350 nT in the North. We believe it unlikely that the difference could be due entirely to a difference in the ionospheric Hall conductivity at the two sites because the observations were made near equinox and the stations are separated by only ~ 2.6 h in MLT and ~ 1.25 h in geographic local time (at conjugate geographic latitudes). Instead we attribute the difference to an asymmetry in the ionospheric flow pattern, due most probably to the large positive component of IMF B_y present at this time. In the southern hemisphere it is thought that this polarity of IMF B_y gives rise to a strong eastward flow component in the cusp region ionosphere

(a)

(b)

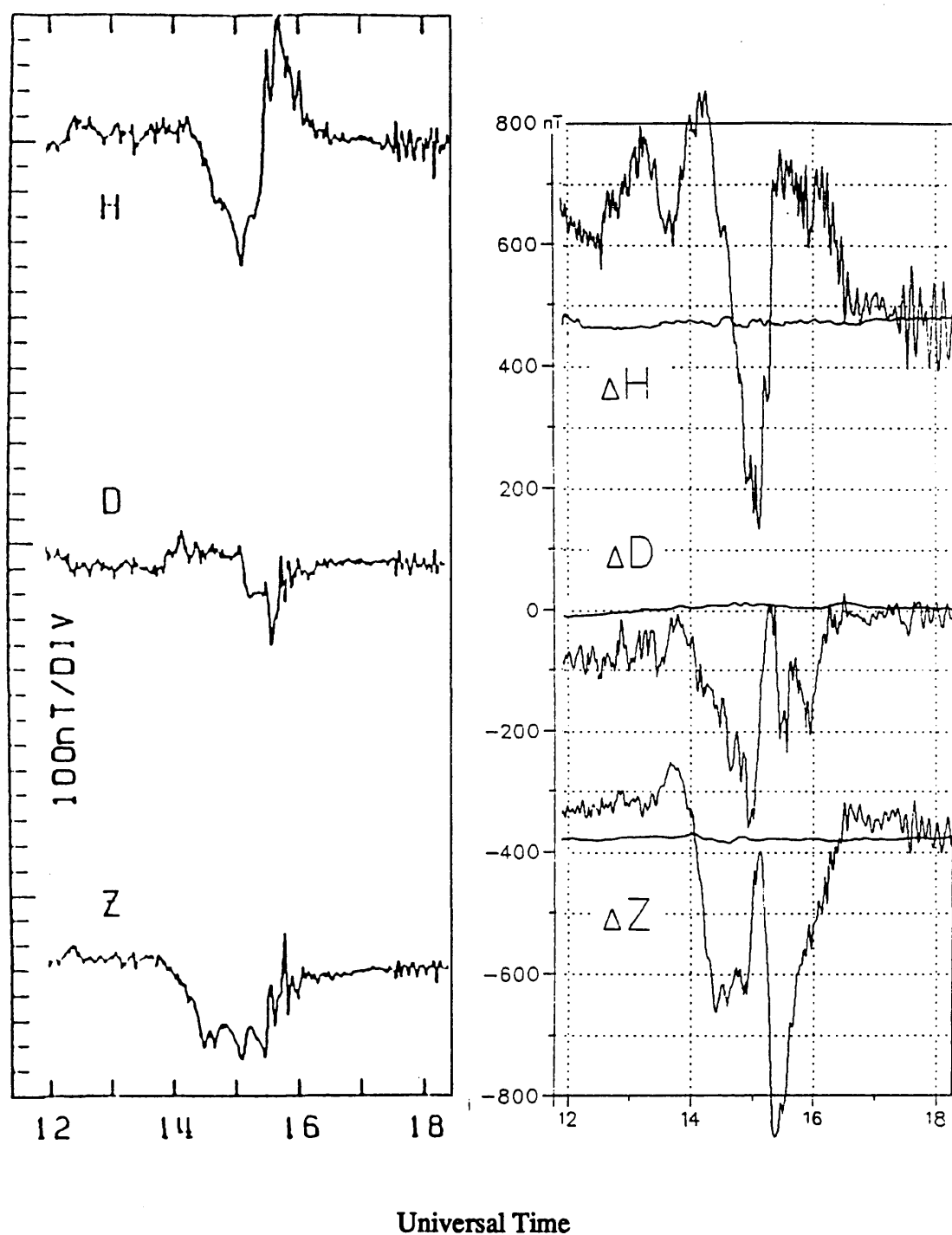


Fig. 4.10. Ground magnetograms from (a) Syowa and (b) Kilpisjarvi, in the southern and northern hemisphere respectively. Each figure shows from top to bottom: north-south (H), east-west (D), and vertical (Z) components, measured in units of nT.

(e.g. Cowley, 1981). In addition, the return flows in the auroral zone at the eastward edge of the cusp region may be weaker. Thus Syowa station, located at $\sim 14:30$ MLT at the time of interest, is likely to be in a local time sector where a large contrast is present between the polar cap and auroral zone flow strengths. The opposite dawn-dusk flow asymmetry in the northern hemisphere for this sense of IMF B_y , means that at Kilpisjarvi the flow magnitude is likely to be dominant in the auroral zone, as observed (see below).

The second key difference between the observations at the two stations is the times of polarity reversal in the inferred east-west flow component. It can be seen that the negative bay in the H component recorded at Kilpisjarvi is nested within the negative bay recorded at Syowa. Using the simplest assumption that the ground magnetic perturbation is due to the overhead current, this observation would imply that the east-west flow reversal that we associate with the polar cap boundary moved equatorward to cross Syowa earlier than Kilpisjarvi, then subsequently moved poleward, reversing the temporal sequence. Since Syowa is at a higher geomagnetic latitude than Kilpisjarvi, the observation is qualitatively consistent with the nested radar and magnetometer data from Syowa alone and illustrates the large-scale, conjugate nature of the phenomenon. The lag between the reversal observations at the two sites yields an equatorward motion of $200\text{--}300\text{ m s}^{-1}$. However, at this point it is important to recognise the asymmetry in the east-west flow shear across the polar cap boundary at Syowa, that was of opposite sense at Kilpisjarvi. Thus, as mentioned in section 4.2.3. (ii), when we consider the integrated effect of the whole current field in the ionosphere around a station, and not just the contribution from directly overhead, large (small) polar cap flows relative to those in the auroral zone have the effect of displacing the position of the H component reversal equatorward (poleward) relative to the actual flow reversal boundary. Thus to successfully employ magnetometer data to locate the position of the flow reversal boundary it is important to have knowledge of the latitudinal variation of the ionospheric flow field. The Scandinavian chain, of which Kilpisjarvi is a part, allows us to measure the flow field along a meridian and hence can be used to assess more accurately the effect of this systematic error on the estimated position of the flow reversal boundary.

In order to determine the ionospheric current distribution from the ground it is necessary to accurately measure the perturbations in the geomagnetic field arising due to these currents. To do this, we subtract the ambient geomagnetic field from the disturbed field at each station. We define the ambient field as that prevailing in the absence of ionospheric currents driven by solar wind-magnetosphere coupling. This was evaluated for each station by averaging the geomagnetic field measurements between 10:00 UT and 16:00 UT on a quiet day (August 22, 1984; $\Sigma K_p = 2-$, $K_p(\text{max}) = 0+$) as close as possible to the magnetically active day in which we are interested (September 4, 1984; $\Sigma K_p = 36+$,

$K_p(\text{max}) = 8$). As an example, the geomagnetic field recorded at Kilpisjarvi on August 22, 1984 is shown in Fig. 4.10b by the lighter trace. It is evident that the field was very steady, and thus the magnetosphere very quiet, throughout this day. The small deviations that were present may be due to solar-driven tidal motions in the ionosphere e.g. the SQ current system (Akasofu and Chapman, 1972). To account for these we estimate their amplitude by measuring the maximum deviation in each geomagnetic field component between 10:00 UT and 16:00 UT on the quiet day. All were less than 20 nT, except for one (~ 35 nT).

The only remaining effect which is then likely to alter the ambient field significantly is the Earth's ring current. The error associated with this will be less than the difference in the D_{ST} index between the quiet and disturbed days (over the interval of interest, 10:00 - 16:00 UT). The values are $D_{ST} = (11 \pm 3)$ nT and $D_{ST} = -(21 \pm 21)$ nT respectively. Assuming the ring current to be in the equatorial plane centred at 5 R_E , we estimate, from geometrical considerations, the systematic error due to the ring current to be $\Delta Z = (27 \pm 18)$ nT and $\Delta H = -(7 \pm 4)$ nT. The systematic error in the H component is small compared to the random error in the perturbation field measurement. In addition, the field perturbations during the period of interest on September 4, 1984 were generally well in excess of 100 nT. Thus we shall only consider random errors in the derivation of our results, though remaining conscious of the effect of systematic errors.

We are now able to determine the latitudinal variation of ground magnetic perturbations at any given time for the local time sector of the Scandinavian array. For a uniform ionosphere permeated by a vertical magnetic field the ground magnetic perturbation is due only to the Hall currents (Fukushima, 1969). The solenoidal current system formed by the field-aligned and Pedersen currents has no effect below ionospheric heights. Fig. 4.11a presents instantaneous measurements of the north-south (X) field component perturbation over the latitudinal chain, representing the distribution of east-west Hall currents overhead, at 13:40 UT, 14:00 UT and 14:30 UT. The abscissa is the calculated field perturbation with respect to the quiet time level, and the ordinate is the geomagnetic latitude of the recording station. The error bars represent the random errors in the perturbation measurement. A key is provided at the base of the figure.

To construct this figure we have converted the magnetometer data into a coordinate frame that we believe to be a better description of the prevailing magnetospheric topology. The DMSP observations (see 4.2.2. (iii)) indicated that the generally circular polar cap was displaced $\sim 5^\circ$ anti-sunward with respect to the geomagnetic pole. As in Chapter 2, we use this displaced spherical polar coordinate system to order the data.

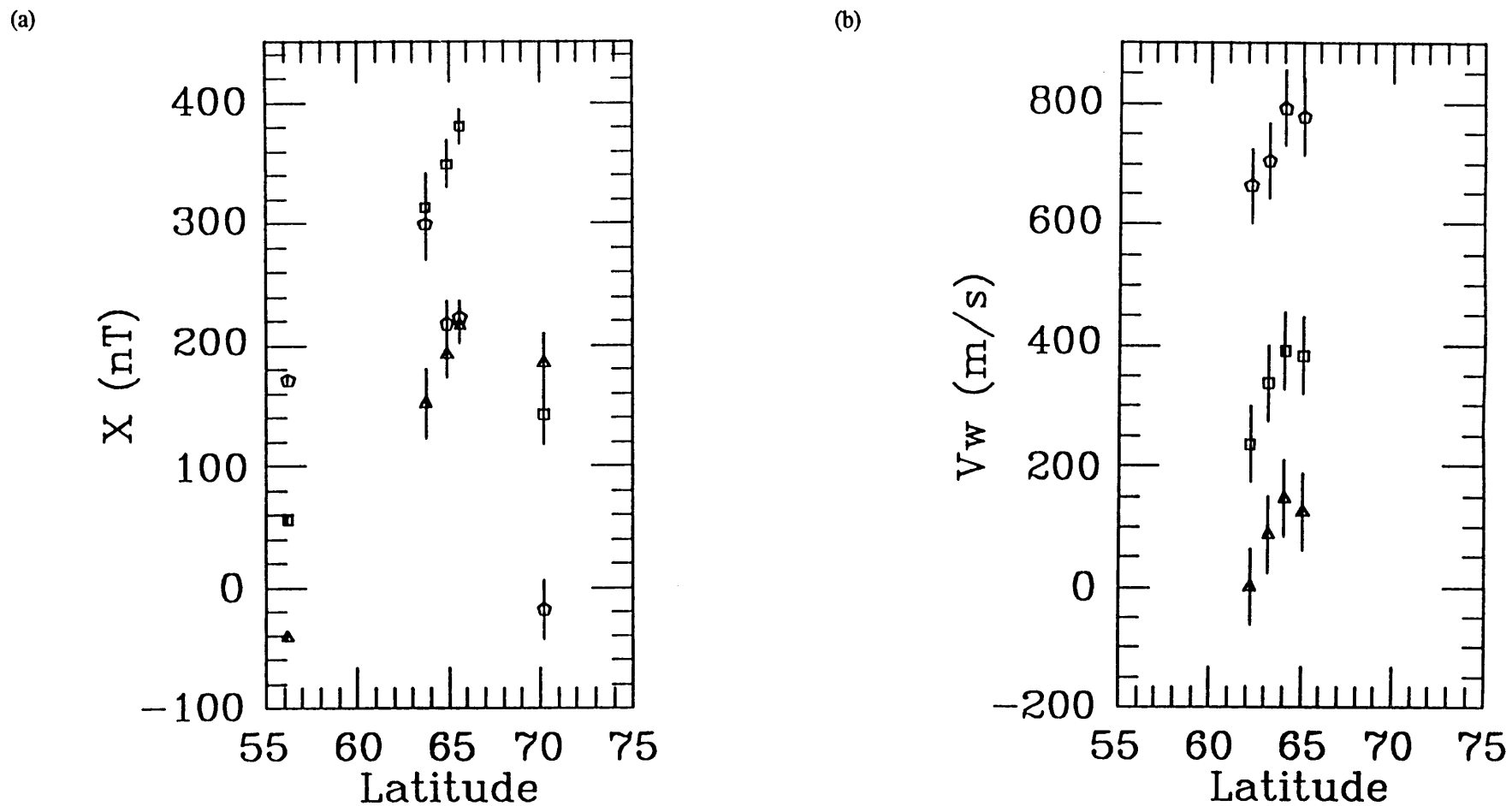


Fig. 4.11. Latitudinal profiles of (a) the northward geomagnetic field perturbation, X , in Scandinavia, and (b) the westward E-region electron drift speed, V_w , estimated by the SABRE radar. Measurements were taken at 13:40 UT (triangles), 14:00 UT (squares) and 14:30 UT (pentagons) on September 4, 1984. See text for further details.

Examination of the figure reveals two systematic effects. Firstly, the peak positive magnetic perturbation was similar at 14:00 UT and 14:30 UT, and greater than that at 13:40 UT. Secondly, the location of the peak appears to have moved equatorward over the interval, from $\sim 66\text{--}70^\circ\text{N}$ at 14:00 UT to $\sim 56\text{--}64^\circ\text{N}$ at 14:30 UT. In association with this the location of the polarity reversal in the X component also moved equatorward. Initially it was sited poleward of the magnetometer chain, but by 14:30 UT it was to be found at $\sim 68^\circ\text{N}$.

With the approximation that the ground magnetic deflection depends only on the ionospheric Hall current immediately overhead and assuming the Hall conductivity to be uniform, the measurements represent the westward ionospheric flow speed profile with latitude over the interval. Thus the convection in the afternoon flow cell is seen to have increased promptly following the southward turning of the IMF recorded by ISEE 2 at 13:38 UT and remained strong thereafter. During the time that the IMF remained strongly southward (13:38 - 15:00 UT), the auroral zone moved equatorward. By 14:30 UT eastward flows were recorded poleward of $\sim 68^\circ\text{N}$ corresponding to the anti-sunward plasma motion on open field lines in the polar cap. We now see that the variation in the magnetic perturbation at a given station is due predominantly to the relative motion of the station with respect to the convection pattern, rather than to changes in the convection strength.

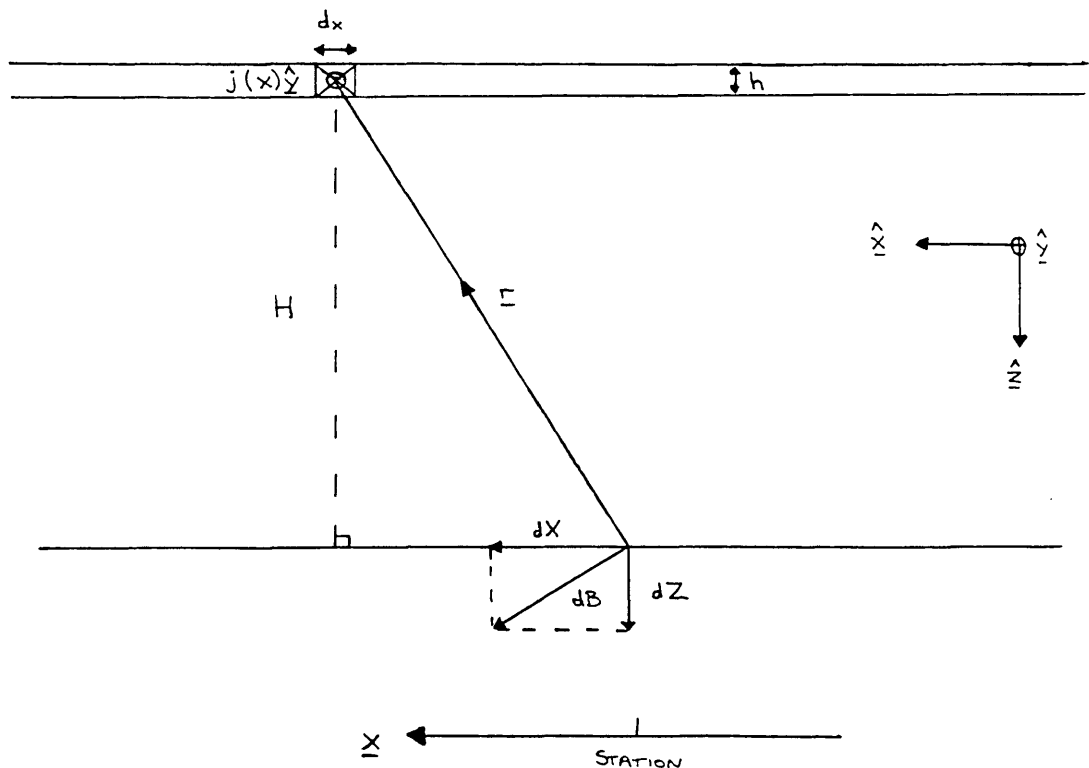


Fig. 4.12. The geometry of a simplified ionospheric Hall current distribution and its ground magnetic effect.

To assess the validity of the above approximation we can use the latitudinal range of the observations to take into account the effect on the ground magnetic perturbation at a particular station of currents off zenith. We consider a spatially varying ionospheric current distribution, but which is simplified in the following ways. The Hall currents are assumed to flow parallel to the (plane) Earth's surface. Additionally we assume that the currents are directed only in the east-west (y) direction and that the current strength varies only in the north-south (x) direction i.e. $\mathbf{j} = j(x) \cdot \hat{\mathbf{y}}$. The arrangement is shown in Fig. 4.12, together with the field perturbation arising from a line current element displaced in the x direction relative to the recording station. Applying Stokes' theorem to Maxwell's equation expressing Ampère's law, we find the strength of the magnetic perturbation to be:

$$B = \mu_0 \cdot j(x) \cdot dx \cdot dh / (2 \cdot \pi \cdot r) \quad (4.1)$$

where the magnetic perturbation is directed in the $\mathbf{r} \times \mathbf{j}$ direction. We can then resolve this perturbation in the directions of $\hat{\mathbf{x}}$ and $\hat{\mathbf{z}}$ and integrate over all the current elements to find the total field perturbation components at the station. These are given by:

$$X = \frac{\mu_0 \cdot h \cdot H}{2} \int \frac{j(x) \cdot dx}{(H^2 + x^2)} \quad (4.2)$$

and

$$Z = \frac{\mu_0 \cdot h}{2} \int \frac{j(x) \cdot x \cdot dx}{(H^2 + x^2)} \quad (4.3)$$

where H is the height of the thin (thickness, $h \ll H$) Hall current layer above the Earth's surface.

If the ionospheric Hall current sheet is spatially uniform and of infinite extent then we find that the vertical magnetic perturbation at the ground is zero and the horizontal perturbation, X_∞ , is given by:

$$X_\infty = 1/2 \cdot \mu_0 \cdot B_I \cdot \Sigma_H \cdot v \quad (4.4)$$

where B_I is the ambient ionospheric field strength, Σ_H is the uniform height-integrated Hall conductivity, and v is the uniform $\mathbf{E} \times \mathbf{B}$ drift speed. We find that in this case 80 % of the magnetic perturbation is from a region of ionosphere within ± 330 km of zenith.

The above results assume that ground induction effects due to the temporal variation of the ionospheric Hall currents and the finite conductivity of the Earth's surface are negligible. If the Earth were a perfect dielectric then this would be so. However, for the low frequency (period, τ) variations that we observe i.e. $1 \text{ min} < \tau < 1 \text{ h}$, we find that the Earth's

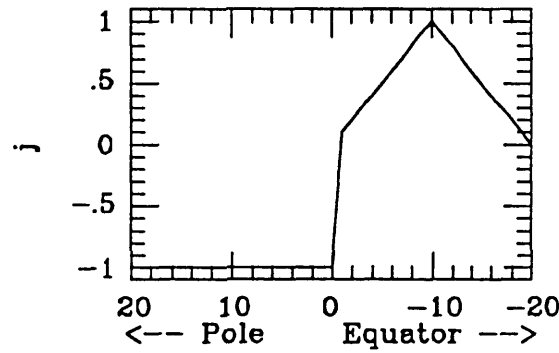
surface is in fact a good conductor. In the limit of a perfectly conducting uniform Earth, the magnetic field parallel to its surface measured by a ground station would tend to twice that measured in the absence of induction effects i.e. the factor of 1/2 in equation (4.4) would tend to unity. Additionally, any component of the magnetic field normal to the surface would tend to zero. However, this assumes that the thickness of the conductor is infinite. When the thickness is smaller than the skin depth of the conductor then the vertical perturbation can be non-zero and the numerical factor in equation (4.4) lies between 0.5 and 1 (Boteler, 1978). Boteler quotes results for an inducing field of wavelength 1000 km which indicate that the vertical perturbation is suppressed to ~ 40 % of its normal value and the horizontal perturbation is enhanced by ~ 60 % when the depth of the surface layer (in this case the sea) is 6 % of the skin depth. However, since we observe vertical perturbations comparable to the horizontal ones (see Fig. 4.10), we conclude that the skin depth is much larger than the effective conducting layer. This is undoubtedly so in the case of ice (e.g. at Syowa) which has a skin depth, $\delta > 1200$ km for $\tau > 1$ min. For a sedimentary rock layer of typically a few km depth we find that $\delta \sim 20$ km for $\tau = 1$ min and $\delta = 140$ km for $\tau = 1$ h, and so equation (4.4) is likely to be reasonable for $\tau > 10$ min. If the basement rock of typical depth 400 km was exposed then we find that $\delta < 430$ km for $\tau < 1$ h and thus in this case we approach the ideal situation where the vertical component is effectively suppressed. At the Scandinavian sites this is manifestly not the case (see Fig. 4.10b).

In Fig. 4.13a we show an idealised latitudinal profile of the eastward Hall current strength. The zero position on the distance axis is chosen to be at the current reversal boundary. Poleward of this the (polar cap) current is assumed uniform and westward. However, equatorward of the boundary the (auroral zone) current is eastward and its strength varies with distance from the boundary. At the boundary the flow is zero, increasing linearly to a maximum at 10 units equatorward of it before linearly decreasing to zero again over a distance of a further 10 units. One unit of distance corresponds to the height of the E region ionosphere where the Hall currents flow. This distance is almost equal to one degree of latitude on the Earth's surface. The current strength is normalised such that the peak auroral zone current is equal to unity, which is also the assumed current strength in the polar cap.

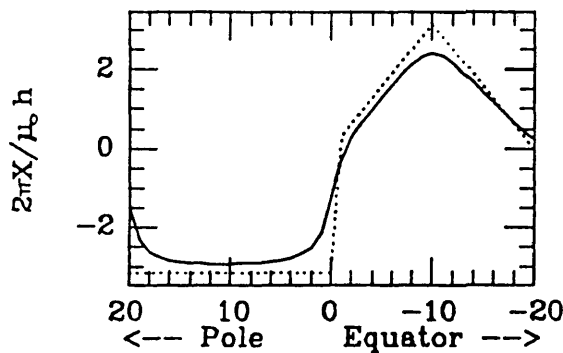
In Fig. 4.13b and 4.13c is shown the X and Z components respectively of the perturbed geomagnetic field arising from the assumed current distribution. Also shown is the magnetic field perturbation due to equation (4.4) using the current strength immediately overhead. The most striking result is the close proportionality between the X field component perturbation on the ground and the current strength directly overhead. Even in the presence of large current gradients this relationship is quite good. This supports the above result that the dominant contribution to the horizontal ground magnetic perturbation is from the Hall currents immediately overhead. This fact is further demonstrated by the close agree-

ment between the X component curve using equation (4.4) and that derived from the current distribution. In particular we note that the asymmetry of the Hall currents about the reversal boundary has the effect of moving the polarity reversal in the X component only ~ 1.5 units equatorward. A potentially more accurate definition of the boundary position in this case is provided by the minimum in the Z component. This is because the Z component is a measure of the Hall current gradient, which we made very large at the boundary in this case. When the normalised polar cap current is reduced to 0.2 units, to simulate a flow asymmetry akin to that expected at the Scandinavian chain, then the reversal offset is reduced to almost zero. In the case of an asymmetry of opposite sense (polar cap current = 1 unit, auroral zone current = 0.5 units), like that expected at Syowa, the offset is increased to ~ 2.5 units equatorwards. This was the maximum possible offset deduced from the Syowa measurements.

(a)



(b)



(c)

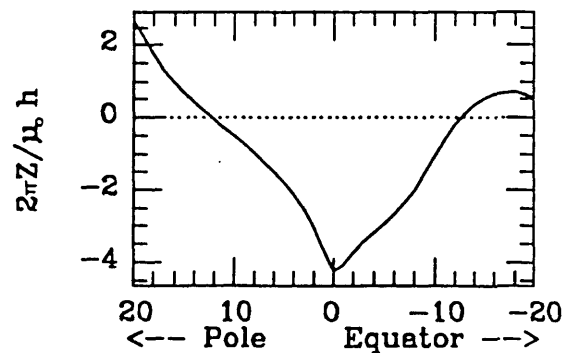


Fig. 4.13. (a) the latitudinal profile of an idealised ionospheric Hall current system. (b) the north-south (X), and (c) the vertical (Z), ground magnetic perturbations resulting from (a), assuming the geometry shown in Fig. 4.12.

Now let us compare the X component arising from the idealised current distribution to the field perturbations actually measured on September 4, 1984, which we presented in Fig. 4.11a. At 14:50 UT we were able to image both sides of the boundary region. We argue that the measurements are qualitatively very similar to those in the modelled case, though the relative amplitude of the auroral zone peak perturbation to that in the polar cap is much larger in the observations than in the model.

Thus we conclude that the temporal evolution of the X field component shown in Fig. 4.11a accurately represents the enhancement and migration of the east-west component of the ionospheric Hall currents. Importantly, we also note that the reversal in polarity of the X component can be estimated to have been located to within $\sim 1^\circ$ latitude of the Hall current reversal for the Scandinavian magnetometers, and to within $\sim 2.6^\circ$ at Syowa. In view of the close proximity of the latter reversal to the energetic particle precipitation boundary from the Syowa station data analysis, we further expect the X component reversal to accurately identify the polar cap boundary.

We interpret the X component data as showing that between $\sim 13:50$ UT and $\sim 15:00$ UT the polar cap steadily expanded and the auroral zone and polar cap boundary moved inexorably equatorward. Although the flow strength increased after 14:30 UT, the qualitative form of the latitudinal flow distribution did not change significantly. Thus a single station magnetogram showing the variation in the ground magnetic field components with time also shows the latitudinal flow profile. We can see, by referring to Fig. 4.10b and Fig. 4.13 that the relationship and form of the X and Z components in the model are very similar to the Kilpisjarvi magnetogram if we assume this relative motion between polar cap boundary and ground station. The Z component reached a minimum when the X component was near zero, and when the X component reached its most negative value the Z component was approaching zero. Furthermore, the Y component was strongly negative near to the boundary crossing implying an equatorward flow at the equatorward-moving boundary. Hence we can be left in little doubt that in the hour or so prior to 15:00 UT the polar cap and auroral zone were expanding equatorward at a steady rate.

After 15:00 UT the X and Z components recorded at Kilpisjarvi evolved with time in a manner that was the reverse of the earlier flow pattern growth and expansion. We conclude therefore that at this time the polar cap contracted poleward and the convection strength decreased. The X component perturbations recorded by the Scandinavian magnetometer chain during the interval 15:00 - 15:50 UT indicate the polar cap contraction to have been more rapid than its expansion.

4.2.3. (iv) SABRE radar data.

The Sweden And Britain Radar-aurora Experiment (SABRE) was a bistatic VHF radar facility. The Doppler shift of coherent echoes from a naturally occurring instability in the E-region ionosphere was used to measure the line-of-sight velocity along 16 beams at each radar site. In the overlapping field of view of the two radars the line-of-sight measurements could be combined to calculate the horizontal ionospheric vector velocity field. However, the principal instability which generates the plasma waves responsible for the radar backscatter only arises when the E region electric field exceeds a threshold of $\sim 15\text{--}20 \text{ mV m}^{-1}$ (e.g. Fejer and Kelley, 1980), equivalent to an electron drift speed of $300\text{--}400 \text{ m s}^{-1}$.

The location of the combined field of view extends between 63.6°N and 68.6°N geographic latitude (64.0°N - 68.4°N GM latitude) and -0.5°E to 12°E geographic longitude (MLT $\sim \text{UT} + 2.1 \text{ h}$ at the central longitude). Thus the radar was situated $\sim 1 \text{ h}$ of MLT earlier than the Scandinavian magnetometer chain, and covered a range of latitudes within that of the chain. The spatial and temporal resolution of the radar was 20 km and 20 s respectively. The radar is discussed in more detail in Chapter 5.

Fig. 4.14 presents the estimated electron drift velocity in geographic coordinates measured by the radar over the interval 12:00 - 18:00 UT on September 4, 1984. The data was spatially averaged over the area 66.0°N - 67.0°N , 4.0°E - 6.0°E (geographic). The plot has been sub-divided into 5 regimes, each regime representing different flow behaviour.

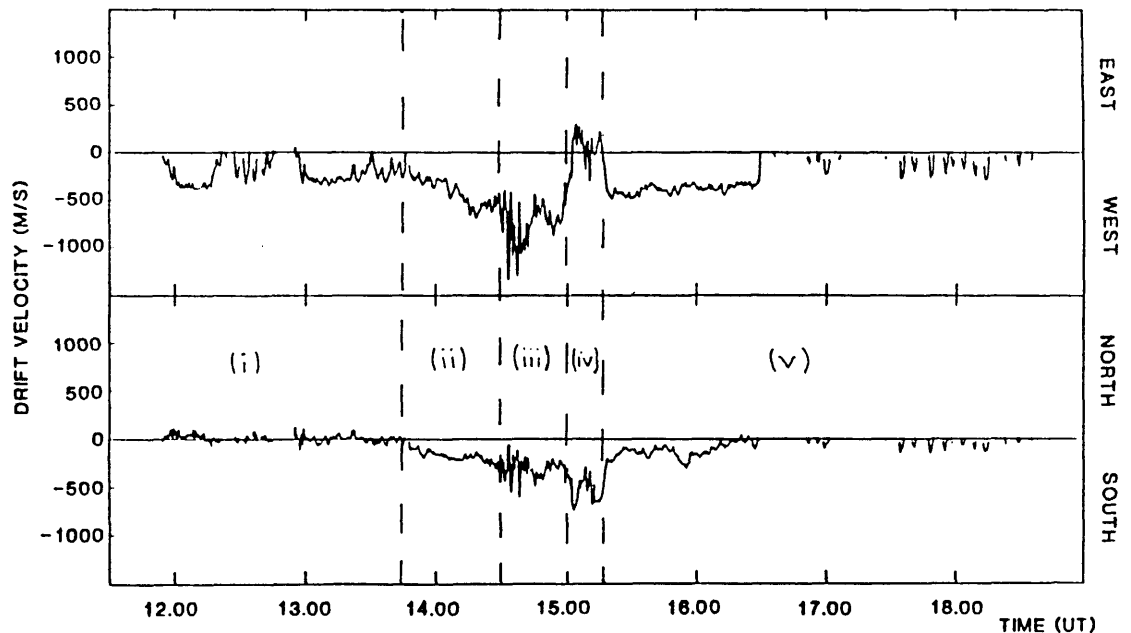


Fig. 4.14. Eastward (V_e ; upper panel) and northward (V_n ; lower panel) ionospheric flow components recorded near the centre of the SABRE field of view over the interval 12:00 - 18:00 UT on September 4, 1984.

In regime (i), 12:00 - 13:45 UT, the flows were intermittent. However, the absence of flows does not necessarily mean that the ionospheric plasma came to rest, only that it fell below threshold. Thus during this period the flow was probably continuously close to the threshold of $300\text{--}400\text{ ms}^{-1}$. The flow was directed almost purely westward, consistent with the radar being in the afternoon auroral zone flow cell.

At 13:45 UT the flows suddenly picked up. During regime (ii), 13:45 - 14:30 UT, the flow speed steadily increased from $\sim 300\text{ ms}^{-1}$ at the start of the interval to $\sim 600\text{ ms}^{-1}$ at the end. Though predominantly westward, there was a sizeable equatorward component to the flow.

Large pulsations were recorded on an increasing background flow near 14:30 UT, marking the beginning of regime (iii), 14:30 - 15:00 UT. After the oscillatory activity the flow field exhibited a strong latitudinal shear with high-speed, westward flows in the southwestern region of the SABRE field of view and low-speed, south-westward flows in the north-eastern sector. The sharp reorientation of the flow across the field of view is thought to be due to a Region II field-aligned current sheet which was established during the pulsation event (Waldock et al., 1988). A detailed examination of this phenomenon is carried out in Chapter 5.

In the north-eastern sector of the field of view nearest to the Scandinavian magnetometer chain the flows (not shown) steadily decreased and rotated equatorward in a manner similar to that seen between $\sim 14:10$ UT and $\sim 14:45$ UT at Kilpisjärvi (see Fig. 4.10b). To quantitatively compare the two data sets we present in Fig. 4.11b the westward flow speed spatially averaged over three narrow (1°) latitudinal bins and over the longitudinal range $5\text{--}7^\circ\text{E}$ (geographic). The measurements were taken at the same times as at the magnetometers and the velocity scale has been chosen such that 2 ms^{-1} on Fig. 4.11b is equivalent to 1 nT on Fig. 4.11a. Using equation (4.4), the proportionality between the electron drift speed and the field perturbation implies a height integrated Hall conductivity of $\sim 16\text{ mho}$. This is similar to the conductivity value obtained for the overhead ionosphere at Syowa and is about equal to the Hall conductivity expected in this region (Wallis and Budzinski, 1981). In Chapter 2 we showed that with this approximation there is good agreement between the flows at SABRE and those inferred from the magnetometer data at 14:30 UT. However, at 14:00 UT the radar flow speed was significantly lower than that inferred from the magnetometer perturbation using the above relationship. This indicates that at this time, or in this region (the equatorward edge of the auroral zone) the conductivity was $\sim 50\%$ greater than that assumed above, or that equation (4.4) was invalid. The former explanation seems more likely; we have found equation (4.4) to be a good approximation to the horizontal magnetic perturbation due to a distributed current (see

Fig. 4.13b) and the observed large vertical magnetic perturbations indicate that ground induction effects are small. In addition, at 14:00 UT, the Syowa ionogram did indeed show a high electron concentration in the auroral zone E region.

In summary, we interpret the SABRE data over regimes (ii) and (iii) as showing evidence for the equatorward motion of the auroral oval over the SABRE field of view. By 15:00 UT, when the flows were below threshold over the whole of the field of view poleward of 67°N GM latitude, we anticipate the flow reversal boundary to be within this northern sector.

In regime (iv), 15:00 - 15:17 UT, a complete reconfiguration of the flow was observed over the whole SABRE field of view. Referring to Fig. 4.14 the flow in the centre of the field of view was predominantly equatorward with a small eastward component. Examination of the whole field of view during this time reveals that at this local time ($\sim 17:05$ MLT) there was a systematic rotation of the flow from south-eastward near the poleward edge of the field of view, through southward in the central region, to south-westward near the equatorward edge. In this interval the Scandinavian magnetometers all recorded a rapid decrease in the equatorward equivalent flow component, as can be seen by the rapid decrease in the negative Y perturbation recorded at Kilpisjarvi (Fig. 4.10b). At most stations the X component remained largely unchanged initially, recording an eastward flow at all stations except the lowest latitude station, Nurmijarvi, where the flow was strongly westward. However, in the second half of regime (iv) the central three stations observed an approximately shear flow reversal boundary move rapidly poleward over them (see Fig. 4.10b). Thus the dramatic reorientation seen at SABRE appears to have been a local effect. We argue that the phenomenon was due to the field-aligned currents of magnetospheric origin established at this location during regime (iii) which decayed on the time scale of regime (iv) following a rapid change in the magnetospheric boundary conditions on the nightside and dayside.

Steady, predominantly westward flow was present over the period 15:17 - 16:30 UT within regime (v) (15:17 - 18:00 UT). By 15:40 UT the same auroral zone flows were observed by the Scandinavian magnetometer chain. After 16:30 UT the flow fell below the radar threshold, except for periodic flow enhancements towards the end of the interval which were also seen clearly in the magnetometer data in both hemispheres (see Fig. 4.10). Their observation at magnetic local times near the dusk meridian suggests that they may be due to the Kelvin-Helmholtz instability being operational at the magnetopause (Southwood, 1968).

In conclusion, we have found that the SABRE electron drift velocity data reflects and confirms the qualitative ionospheric flow pattern evolution at this local time inferred from

the Scandinavian ground magnetometer chain. We have found that, ~ 8 min after the IMF turned southward at ISEE 2 the ionospheric flows observed by SABRE began to steadily increase. The short ionospheric response time (ISEE 2 - subsolar magnetopause lag ~ 3 min; see section 4.3) is in good agreement with the results of Etemadi et al. (1988) and Todd et al. (1988). The flow turned progressively more equatorward at high latitudes within the field of view and the local westward flow component began to decrease. By 15:00 UT the flow strength was below threshold over the upper half of the SABRE field of view. This systematic behaviour was consistent with the radar viewing the poleward edge of an expanding auroral oval, consistent with the polar cap expansion observed in the magnetometer data and elsewhere (see Fig. 2.10). As the oval moved equatorward a localised field-aligned current sheet generated large latitudinal flow shears.

At 15:00 UT there was a rapid reorientation in the flow generating a semi-vortical flow structure persisting for ~ 20 min. This was apparently local to the SABRE field of view and is thought to be due to the field-aligned current sheet established earlier. Subsequently, the radar viewed typical afternoon auroral zone flows consistent with the magnetometer data observation of a contracted polar cap by this time.

4.3. Discussion.

Ground magnetometer data have shown that on September 4, 1984, the afternoon cell convection pattern steadily intensified and expanded between 13:50 UT and 15:00 UT. The inferred flow behaviour was supported by neighbouring radar measurements.

After 15:00 UT the magnetometer and radar data showed a more rapid shrinkage of the afternoon cell convection system and a slow decline in the circulation strength over the next few hours.

The change in size of the convection system was shown to be intimately related to the growth and decay of the polar cap or open field line region. At Syowa station the entry into the weak precipitation region of the polar cap closely coincided with the detection of anti-sunward flows by the co-located magnetometer. Particle data from both the DMSP polar orbiting satellite and ionosondes showed the equatorward motion of the cusp/cleft as the convection system expanded and the subsequent poleward retreat on flow cell contraction.

The low-altitude particle and flow data can be usefully combined to trace the motion of the polar cap boundary throughout the interval of interest on September 4, 1984. A locus of points closely corresponding to the polar cap boundary is shown in Fig. 4.15, where the abscissa is latitude and the ordinate is Universal Time. The latitude scale represents that

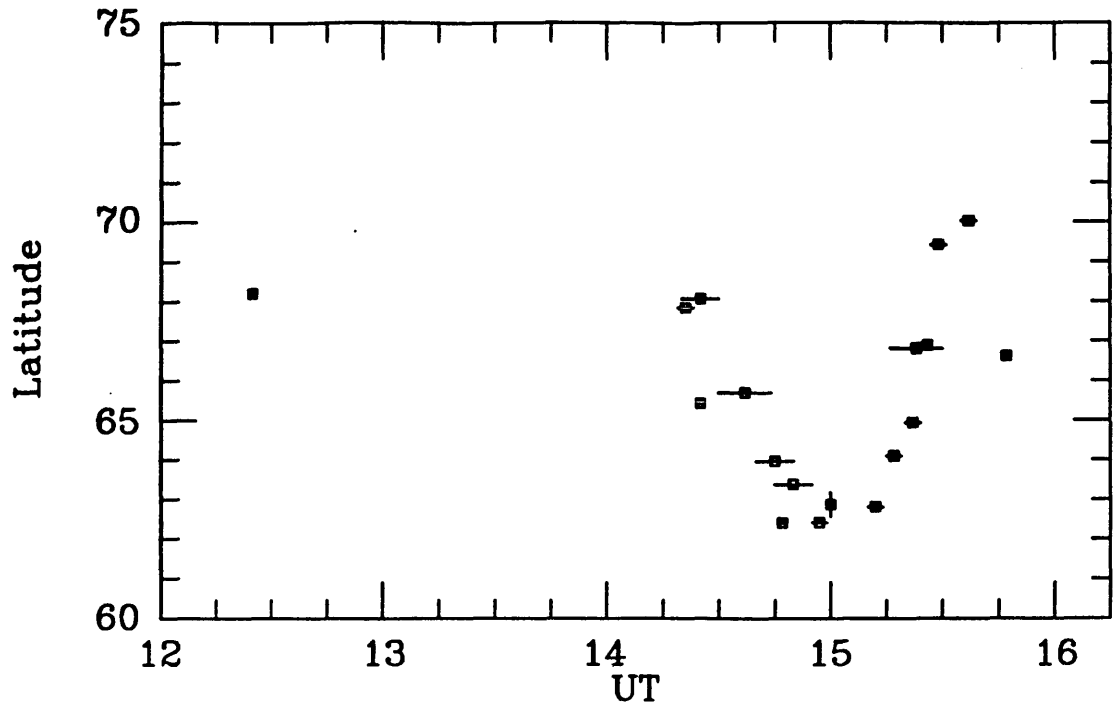


Fig. 4.15. Estimated location of the polar cap boundary versus Universal Time (UT) on September 4, 1984. The latitudinal scale represents the boundary position in a polar cap centred coordinate system (see text).

in a polar cap centred coordinate system where the polar cap is offset with respect to the geomagnetic pole (see Chapter 2). Qualitatively, the same global boundary motion can be inferred from data plotted in the geomagnetic frame. However, data from widely separated sites are in better agreement when the polar cap centre is displaced $\sim 7^\circ$ anti-sunward and rotated ~ 1 h towards dawn (dusk) in the northern (southern) hemisphere.

The following measurements were used to characterise and locate the polar cap boundary:

- (i) Reversal in the X component of the perturbed geomagnetic field - as discussed above this is expected to closely match the position of the east-west flow reversal which, in the absence of viscous boundary effects, should be co-located with the polar cap boundary. Modelling of an asymmetric latitudinal flow profile in the mid- to late afternoon local time sector has shown that the magnetic field reversal may place the flow reversal up to $\sim 2^\circ$ away from its true position.

(ii) Ionosonde data - entry by the observing site into the polar cap was identifiable by the cessation of energetic particle precipitation into the D- and E-region ionosphere. On the figure the period between the observation of auroral oval and polar cap particle fluxes is shown.

(iii) Polar orbiting satellite particle data - the position of the equatorward edge of the cusp is indicated, which is expected to correspond to the polar cap boundary. The data were discussed in detail above.

The figure clearly illustrates the steady equatorward motion of the polar cap boundary over ~ 1 h up to 15:00 UT and its subsequent rapid poleward contraction over ~ 30 min to a latitude higher than that prior to expansion. The observation of the cusp near noon MLT at a minimum GM latitude of $\sim -66^\circ$ by the Halley ionosonde is in good agreement with the expected position of the most equatorward arc in this local time sector based on the results of Chubb and Hicks (1970) discussed earlier. At the beginning and end of the interval the nightside auroral oval was located $\sim 10^\circ$ GM latitude further equatorward than on the dayside. By taking into account the tilt of the polar cap centre towards the nightside with respect to the geomagnetic pole we have shown that ground measurements of the polar cap boundary position from widely separated sites in the northern and southern hemisphere are in good agreement when the polar cap is assumed circular and displaced 7° anti-sunward of the geomagnetic pole. Since ground data sets were limited to the afternoon sector we were comparing distinctly different convection patterns. Under the strong IMF By prevailing at the time of the polar cap expansion it is thought that a strong asymmetry in the ionospheric convection pattern should be produced. We have already commented on the observation that the flow pattern exhibited this asymmetry: the afternoon flow cell in the southern hemisphere is expected to reflect the situation in the northern hemisphere morning cell, which differs from that in the northern hemisphere afternoon cell (Heppner and Maynard, 1987). In addition, the morning cell, northern hemisphere cusp observation by the DMSP satellite at 14:47 UT is also in good agreement with the ground data results, further supporting this model of the polar cap expansion.

Finally, we address the question of what caused the polar cap expansion and contraction? The increase in the convection strength and the start of the polar cap expansion was first detected by the Scandinavian magnetometer chain at $(13:45 \pm :01)$ UT (see Fig. 4.10b) and at about the same time at SABRE (see Fig. 4.14). This followed a southward turning in the IMF detected at ISEE 2 at $(13:37 \pm :01)$ UT when the spacecraft was $6.7 R_E$ upstream of the Earth. At 13:19 UT, just prior to the bow shock crossing of the AMPTE-IRM spacecraft, the solar wind dynamic pressure was measured to be (12.1 ± 1.4) nPa. Assuming the magnetopause subsolar point to be determined by a pressure balance between the

solar wind dynamic pressure and the compressed geomagnetic field, we predict the magnetopause stand-off distance to be $(7.1 \pm 0.3) R_E$ based solely on geomagnetic field pressure, and $(7.5 \pm 0.3) R_E$ when geomagnetic field curvature forces are taken into account (Mead and Beard, 1964). Considering the effect of the IMF on the solar wind flow to be negligible Spreiter and Stahara (1980) calculated the subsolar bow shock distance normalised to the subsolar magnetopause distance, D , for different solar wind Mach numbers. It is calculated that the solar wind Mach number at IRM just prior to bow shock encounter was 6.4 ± 0.7 . Thus the subsolar bow shock distance is predicted to be at $(1.285 \pm 0.008) D$, equivalent to $(9.1 \pm 0.4) R_E$ or $(9.6 \pm 0.4) R_E$ using the estimated magnetopause locations calculated above. If we assume the phase front of the IMF B_z change to propagate at the local flow speed and be aligned perpendicular to the Earth-Sun line, the latter approximately parallel to the solar wind velocity vector, then the front was detected at ISEE 2 (40 ± 10) s after it impacted upon the subsolar bow shock. The assumption of a perpendicular phase front was supported by the near-coincident observation of the northward IMF turning by both spacecraft at $\sim 13:20$ UT, as discussed earlier. The time taken for the front to traverse the subsolar magnetosheath region can be estimated by noting that the Spreiter and Stahara (1980) model predicts the solar wind speed to fall by a factor of 4 across the subsolar bow shock and decrease approximately linearly from this point to the subsolar magnetopause. Thus the average convection speed is $1/8$ of the solar wind speed. The latter was measured to be $(459 \pm 17) \text{ kms}^{-1}$ by IRM immediately before its bow shock crossing. Thus the magnetosheath transit time is estimated to be (230 ± 10) s in both model cases. Hence the magnetopause - station delay at the local time of the Scandinavian magnetometer chain ($\sim 16:00$ MLT) is found to be (290 ± 90) s, a result which is consistent with the ionospheric response time of the east-west flow component to changes in IMF B_z measured by Etemadi et al. (1988) for the same local time sector using a cross-correlation analysis. We argue therefore that it is the southward turning of the IMF that initiates the polar cap expansion and increased convection. The open magnetosphere model of Dungey (1961) is also therefore the best description of the observed phenomena since it has the same correlation between the magnetosphere-ionosphere convection and the southward component of the IMF.

As argued in Chapter 2 and in the introduction of this chapter, in the open magnetosphere model we expect that for a dayside reconnection rate in excess of that on the nightside the amount of open magnetic flux will increase, causing the polar cap area to increase. The increase in open flux will be at the expense of the closed flux and thus we might expect the dayside magnetosphere to shrink and the dayside magnetopause to move earthward as the tail flux increases. Coincident with the observation of an increasing polar cap area, the AMPTE-IRM spacecraft encountered the magnetopause boundary layer. In our discussion of the data set we pointed out that the observations of field and plasma across the

boundary were shown by Paschmann et al. (1986) to satisfy the stress balance conditions for a reconnected field line threading the magnetopause. Thus it was concluded that reconnection was ongoing at the time of magnetopause encounter. Furthermore, the boundary layer was continuously observed by the spacecraft for a prolonged period, during which it had traversed $\sim 0.5 R_E$ earthward. This sustained encounter suggests that the magnetopause over this period was moving earthward with the spacecraft, and hence the dayside magnetosphere was shrinking. We shall now show that this motion was not attributable to a change in the solar wind dynamic pressure, but must instead be due to magnetospheric erosion by enhanced magnetic reconnection on the dayside. In fact we shall show that the erosion was at a rate even greater than that equivalent to the spacecraft speed and was comparable with the erosion rate inferred from the polar cap expansion observed on the ground.

Firstly we consider the boundary locations expected on the basis of the work of Mead and Beard (1964) and Spreiter and Stahara (1980) for the prevailing solar wind conditions just prior to the IRM bow shock encounter and compare these with the observations. As mentioned above, the solar wind dynamic pressure at 13:19 UT was measured by the IRM spacecraft to be (12.1 ± 1.4) nPa, and the solar wind Mach number was found to be 6.4 ± 0.7 . The subsolar magnetopause distance was therefore calculated to be in the range, $D \sim 7.1 - 7.5 (\pm 0.3) R_E$, depending on the level of approximation employed. At the local time of the IRM bow shock crossing the Spreiter and Stahara (1980) gas-dynamic model would predict the shock to be at a radial distance, $(1.52 \pm 0.02) D$. Thus the two limiting positions of the bow shock would be $(10.8 \pm 0.5) R_E$ and $(11.4 \pm 0.5) R_E$. The actual IRM crossing distance was at $9.96 R_E$, $\sim 1 R_E$ within these estimates. However, we note that the IRM bow shock crossing distance is a minimum estimate since we cannot be sure that the solar wind conditions were steady and thus the bow shock may well have been moving outwards past the spacecraft. Alternatively, the discrepancy may be due to some erosion of the magnetosphere even at this early stage.

At the time of the IRM bow shock crossing the magnetopause in the spacecraft local time sector is predicted by the two models to be at a radial distance, $d = (8.2 \pm 0.4) R_E$ or $d = (8.7 \pm 0.4) R_E$, depending on approximation level. On cursory inspection this agrees quite favourably with the actual IRM initial magnetopause encounter at $8.04 R_E$, assuming the solar wind dynamic pressure to have remained constant during the magnetosheath crossing. However, referring to Fig. 4.4b, it is evident that the upstream conditions were not steady. Between $\sim 13:45$ UT and $\sim 13:55$ UT there was a large decrease in the magnetosheath density and speed. Over this period the magnetosheath dynamic pressure dropped by an order of magnitude, considerably larger than the decrease ($\sim$ factor of two) in dynamic pressure across the steady state magnetosheath at this local time. The size of

the decrease and the positive radial gradient in dynamic pressure within the magnetosheath at the IRM local time means that the dynamic pressure drop recorded by IRM can only have been caused by a change in the solar wind dynamic pressure. Hence the magnetospheric system must have expanded at this time and thus the agreement between the estimated and observed magnetopause positions is not as good as might first have been thought. Rather it seems that dynamic pressure effects alone cannot account for the location of the magnetopause when encountered by the IRM.

From the Spreiter and Stahara (1980) gas dynamic model we expect the magnetosheath dynamic pressure recorded by the IRM to fall from a value, $\beta_0 P$, at the bow shock (time t_0) to $\beta_1 P$ at the magnetopause (time t_1), where β_0 and β_1 are parameters determined by the geometry of the magnetospheric system. However, if at the magnetopause we measured a pressure, $P_1(t_1)$, then we may expect the solar wind dynamic pressure to have changed such that:

$$\frac{P(t_1)}{P(t_0)} = \frac{P_1(t_1)}{\beta_1 P} \quad (4.5)$$

But $\beta_0 P(t_0)$ is the dynamic pressure measured by the IRM just inside the bow shock, $P_0(t_0)$. Hence:

$$\frac{P(t_1)}{P(t_0)} = \frac{P_1(t_1)}{P_0(t_0)} \cdot \frac{\beta_0}{\beta_1} \quad (4.6)$$

Immediately after the IRM bow shock crossing the magnetosheath dynamic pressure was, $P_0(t_0) = (20.8 \pm 1.2)$ nPa, and immediately prior to magnetopause encounter this had fallen to $P_1(t_1) = (2.2 \pm 0.3)$ nPa. At the local times of the IRM bow shock crossing and the magnetopause encounter the geometrical parameters are, $\beta_0 = 1.19 \pm 0.03$, and $\beta_1 = 0.69 \pm 0.02$. Thus the revised limits to the magnetopause position at the IRM crossing time are $(10.9 \pm 0.9) R_E$ and $(11.6 \pm 0.9) R_E$. The actual magnetopause encounter was significantly earthward of this location, implying that the magnetopause had eroded due to a cause other than the solar wind dynamic pressure. Even taking into account the possible overestimate of the bow shock position compared with the IRM observation we would still infer significant magnetospheric erosion.

Assuming the model results to be accurate, we conclude that the minimum distance eroded by the magnetopause from its equilibrium position based solely on the effect of the solar wind dynamic pressure is $(3.2 \pm 1.3) R_E$, where the error now includes the range of bow shock distances due to the different magnetopause pressure balance approximations. Assuming the erosion took place over the whole dayside, and approximating the equatorial dayside magnetopause to a semi-circle we can estimate the amount of magnetic flux eroded

from the whole dayside magnetosphere. This is given by $B_{mp} \cdot \pi \cdot (r_1^2 - r_0^2) / 2$, where B_{mp} is the average magnetic field strength in the magnetopause boundary layer and r_1 , r_0 are the uneroded and eroded positions of the magnetopause respectively. Using the values calculated above and $B_{mp} = 100$ nT (see Fig. 4.4b), we calculate the amount of eroded dayside flux to be $(4.0 \pm 0.1) \times 10^8$ Wb. Given that the geomagnetic field strength at the Earth's surface is typically 5×10^{-5} nT, then the area of eroded flux at this height is $\sim 1/32$ of the total northern hemisphere area. Thus if the whole of the polar cap region is supplied by the flux eroded from the dayside magnetosphere then the polar cap boundary on this day would subtend an angle of $\sim 14^\circ$ from its centre. However, at 14:40 UT the polar cap boundary was observed to subtend an angle of $\sim 25^\circ$ about its centre.

We therefore infer that either there exists a polar cap of finite size even when the dayside magnetosphere is uneroded or that the magnetospheric field lines on the dayside reconfigure so as to exert a field tension force, in addition to the field pressure, that acts against the earthward erosion of the magnetopause. In the former case the area of the pre-existing polar cap is calculated to subtend an angle of $\sim 20^\circ$ about its centre.

To avoid the assumption of an uneroded magnetopause position we shall now turn our attention to the flux erosion on shorter time scales. It was noted that during the sustained boundary layer encounter made by the IRM between 14:42 UT and 15:01 UT there was a brief exit of the spacecraft back out into the magnetosheath (see Fig. 4.4b). The dynamic pressure at this time was measured to be (1.1 ± 0.1) nPa, lower than that prevailing just prior to the initial magnetopause encounter. We ascribe the temporary earthward motion of the magnetopause relative to the IRM to be due to an enhancement in the erosion rate. Assuming the spacecraft to have remained close to the magnetopause we can calculate the minimum distance eroded by the magnetopause between 14:42 UT and 14:51 UT, taking into account the observed decrease in dynamic pressure. Although the IRM moved only 0.23 R_E earthward during this period, the magnetopause eroded by $(1.2 \pm 0.6) R_E$. Assuming this rate over the whole dayside region (approximated to be hemispheric), and with a magnetic field strength in the boundary layer of 100 nT, we calculate the magnetic flux erosion rate to be (240 ± 120) kV.

Over the same interval the polar cap boundary was observed to move equatorward across the Scandinavian magnetometer chain at a speed of $(310 \pm 170) \text{ ms}^{-1}$. Assuming the polar cap expansion to be isotropic, the flux addition rate to the polar cap is given by:

$$\frac{d\Phi}{dt} = B_I \cdot 2 \cdot \pi \cdot R_E \cdot \cos\lambda \cdot V_b \quad (4.7)$$

where B_I is the geomagnetic field strength at the Earth's surface, λ is the mean latitude of the polar cap boundary, and V_b is the boundary speed. The flux addition rate is found to be (250 ± 130) kV which is in excellent agreement with that observed at the magnetopause. We note that this value is also in agreement with the cross-throat potential of 230 kV inferred from a comparison of a uniformly expanding polar cap model with ionospheric convection data (see Fig. 2.9).

We have thus shown that, following a southward turning in the IMF, reconnection was initiated at the dayside magnetopause. In the event studied here the reconnection rate at the dayside at first dominated over that in the geomagnetic tail so that the amount of open flux increased steadily. The polar cap expansion drove a stronger twin-cell convection pattern pushing flux tubes away from the merging region equatorward. The decrease in the amount of closed magnetospheric flux was directly observed by the IRM spacecraft as an earthward motion of the magnetopause boundary. On short time scales the rate of this magnetospheric erosion was in good agreement with the rate of increase of open polar cap flux, though the estimated total flux erosion could not account for all of the magnetic flux contained in the polar cap.

Finally, we consider the cause of the polar cap contraction. In Fig. 4.16 we present a ground magnetogram from the Alaskan station, College, for the interval 12:00 - 18:00 UT on September 4, 1984. The station location is given in Table 4.1, and we note that at 15:00 UT the station was in the early morning MLT sector. The most striking feature is the very large ($\sim 3000 - 5000$ nT) negative bay in the H component which commenced at $\sim 14:25$ UT and peaked at $\sim 15:00$ UT. A large negative perturbation in the D component and a large positive perturbation in the Z component were also recorded at the same time. We interpret the negative H perturbation as showing evidence for the development of a strong westward electrojet in this local time sector. The diversion of the cross-tail ring current at substorm onset which triggers the collapse of the magnetotail (see Chapter 1) is thought to give rise to just such an intense westward electrojet, limited in latitudinal and local time extent, in the midnight sector (McPherron et al., 1973). The positive Z perturbation shows the station to be situated poleward of the peak electrojet latitude. The negative D perturbation would then indicate the station to be westward of the central meridian of the electrojet (Kisabeth and Rostoker, 1971).

Before the rapid flow increase there appeared to be a relatively small positive perturbation to the H component of the geomagnetic field at the station. At the same time a higher latitude station, Barrow, in the same MLT sector (see Table 4.1) recorded a larger H perturbation (not shown). The inferred westward flow suggests that the stations may initially have been located within the polar cap.

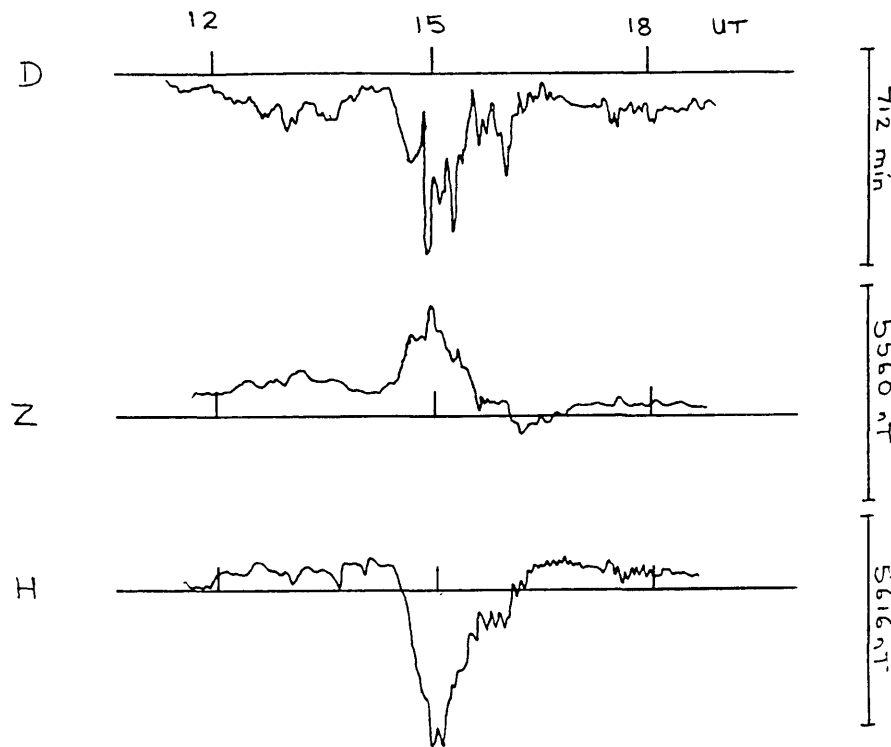


Fig. 4.16. Ground magnetometer data from College, Alaska; 12:00 - 18:00 UT, September 4, 1984. The figure shows from top to bottom: east-west (D), vertical (Z), and north-south (H) components, measured in units of nT.

There seems little doubt that the large nightside magnetic bay was initiated by a rapid enhancement in the reconnection rate in the geomagnetic tail i.e. a substorm. There was ample additional evidence of a substorm at about the same universal time from other data sources. The enhanced reconnection in the tail is an efficient means of converting the stored magnetic energy held in the stressed tail lobe field lines into thermal and kinetic particle energy. The energised particles are transported earthward and can be detected as an increase in the equatorial ring current. The magnitude of the ring current index did indeed rise rapidly between 14:00 UT and 15:00 UT and peaked in the following hour. The energetic particles were also detected directly in the auroral zone region by the DMSP satellite when it traversed the midnight sector near 15:00 UT. After 15:00 UT energetic particle precipitation was also detectable at the foot of dayside closed field lines by the Syowa and Halley Bay ionosondes. The generation of a field-aligned current system at SABRE in the mid-afternoon ionosphere also occurred after the inferred substorm onset. The event is

discussed in Chapter 5 and is argued to be caused by an enhancement of the particle pressure in the outer magnetosphere due to particle injection from the magnetotail.

The effect of the greatly enhanced tail reconnection rate following substorm onset would be to remove open flux from the polar cap, acting against the polar cap expansion due to reconnection at the dayside. The increasing eastward flows were seen first at College at $\sim 14:26$ UT, and reached Barrow at $\sim 14:46$ UT. This represents a northward and westward phase motion, as Barrow is located at higher latitude and earlier local time than College. The lag between the observation of sunward, auroral zone flows at the two Alaskan stations could thus be explained in terms of a rapid ($\sim 400 \text{ ms}^{-1}$) poleward contraction of the polar cap boundary during this period in this local time sector. This is supported by the observation of high energetic particle fluxes over a wide latitudinal range up to $\sim 73^\circ$ GM latitude by the DMSP satellite at $\sim 15:00$ UT. We note, however, that the polar cap boundary on the dayside was still moving equatorward in this interval. Not until the return flows peaked in strength at $\sim 15:00$ UT did the dayside polar cap cease its expansion and begin to rapidly contract as the nightside reconnection rate became dominant over that at the dayside. We recall that at this time the ISEE 2 spacecraft recorded a rapid northward turning of the IMF immediately before the cessation of scientific operations. It is therefore likely that the dayside reconnection ceased just after the nightside reconnection rate reached its peak, thus aiding the net removal of magnetic flux from the polar cap.

4.4. Conclusion.

The observations presented here concur with many of the previously determined features of a substorm sequence (e.g. McPherron et al., 1973). Following a southward turning of the IMF the polar cap is inferred to grow with a concomitant equatorward migration of the enhanced auroral electrojet. After ~ 30 min a large sudden enhancement in the nightside electrojet occurs, indicative of a substorm onset. Energetic particles precipitate into the auroral zone ionosphere and the ring current intensifies. The polar cap contracts rapidly poleward on the nightside and ultimately on the dayside.

This study has increased our knowledge of the substorm cycle by concentrating on the behaviour of the dayside magnetosphere and ionosphere. We have shown the polar cap to expand at a rate in quantitative agreement with the erosion rate of the dayside magnetosphere inferred from spacecraft observations at the magnetopause. We have found that a substorm onset need not have an immediate effect upon the dayside polar cap, though it probably distorts it on the nightside in a manner similar to that envisioned by Akasofu (1977) (see Fig. 2.2). Instead we deduce that the rate of polar cap expansion or contraction is determined by the relative strengths of the dayside and nightside reconnection rates.

CHAPTER 5

MEASUREMENTS OF FIELD-ALIGNED CURRENTS BY THE SABRE COHERENT SCATTER RADAR.

5.1. Introduction.

Field-aligned currents are of central importance in understanding the coupling within the Earth's magnetic system. They are the agents by which momentum may be transferred from the magnetosphere to the ionosphere. Here we outline and discuss an experimental method for their detailed study using ionospheric radar data.

Most measurements of field-aligned currents have used spacecraft magnetometers. Armstrong and Zmuda (1973) identified the magnetic signature characteristic of the large-scale magnetospheric current systems: as a polar-orbiting satellite traversed the afternoon auroral zone an eastward magnetic perturbation was measured over $\sim 2\text{--}3^\circ$ latitude. The observation was interpreted as showing the presence of two oppositely directed current sheets, each aligned along a latitude circle with the poleward current system directed outwards from the ionosphere. In the morning sector the sense of the solenoidal current system was reversed. The global distribution of these large-scale currents was subsequently confirmed by statistical studies (Iijima and Potemra, 1978). The currents were found to intensify and move equatorward with increasing magnetic activity.

The current systems are intimately related to the global magnetospheric convection and arise from the divergent electric fields associated with latitudinal velocity gradients at the poleward and equatorward edges of the auroral zone flow cells (Vasyliunas, 1975). Though the spacecraft observations have been successful in identifying the large-scale magnetospheric current systems, the single point sequential measurements preclude detailed knowledge of their two-dimensional structure and interpretations rely on assumptions about their invariance transverse to the satellite trajectory. In this chapter we show how observations of the ionospheric convection field at high temporal and spatial resolution can be used to measure field-aligned currents and determine their spatial structure. We outline, and discuss the calibration of, an experimental method for the measurement of magnetospheric field-aligned currents using coherent scatter radar data. The technique is used to identify and analyse a localised upward field-aligned current sheet observed in the late afternoon mid-latitude ionosphere. We argue that this current arises from the earthward transport of hot plasma due to ongoing magnetospheric erosion.

5.2. The SABRE Radar.

The Sweden and Britain auroral radar experiment (SABRE) was a bistatic coherent VHF radar facility. The radars were sited in Wick, Scotland and Uppsala, Sweden. Whilst the Wick radar has been in continuous operation from mid-September, 1981 to the present day,

joint two-station operations cover the period, April, 1982 to December, 1986. The location and field of view of the SABRE radars is shown in Fig. 5.1 and will be discussed in more detail later.

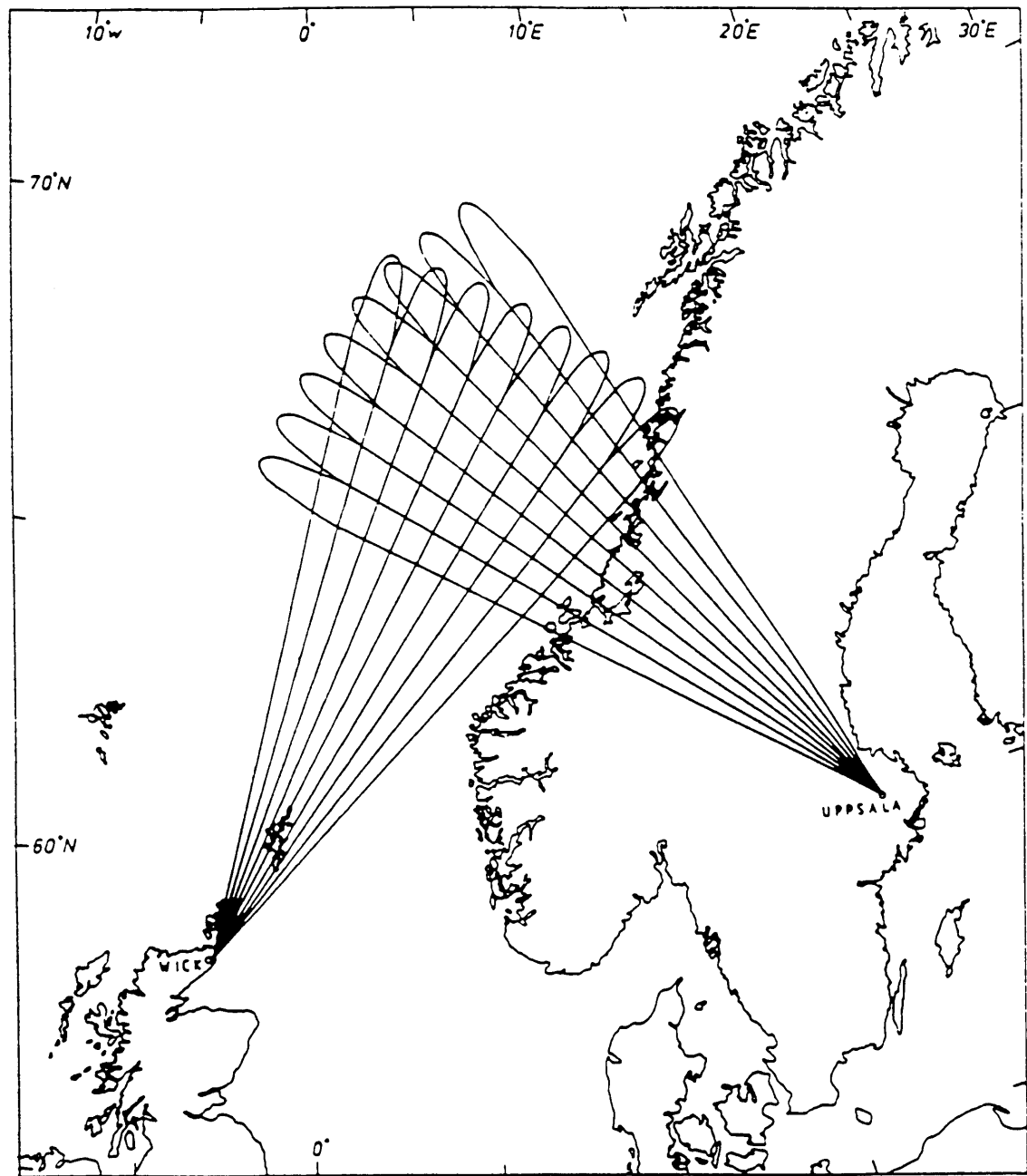


Fig. 5.1. Illustrating the location and field of view of the SABRE radars at Wick in Scotland and at Uppsala in Sweden.

Coherent radars operate by transmitting a radio wave close to perpendicular to the ionospheric magnetic field and then detecting a backscattered signal from non-thermal electron density irregularities in the E region auroral ionosphere. The irregularities are generated by one of two plasma instabilities, both of which arise due to a relative electron-ion drift velocity and a brief discussion of the mechanisms is merited.

In the first mechanism, when the relative electron-ion drift velocity exceeds the ion acoustic velocity then the plasma is unstable to the two-stream instability (Buneman, 1963; Farley, 1963). Free energy is created for wave growth by a net deceleration of particles travelling at close to the wave phase velocity.

The plasma can also be unstable to a macroscopic mechanism, the gradient-drift instability (e.g. Rogister and D'Angelo, 1970). This mechanism requires the convection of plasma by an electric field in the presence of a density gradient orthogonal to the geomagnetic field. Consider a sinusoidal perturbation to a density contour. If the electric field has a component parallel to the density gradient then the relative $\mathbf{E} \times \mathbf{B}$ motion of electrons to ions in the E region ionosphere, due to ion-neutral collisions and associated with the Hall current, will lead to a perturbation polarisation electric field in the direction of the ambient $\mathbf{E} \times \mathbf{B}$ drift. The perturbation electric field drives a perturbation $\mathbf{E} \times \mathbf{B}$ plasma motion which acts so as to enhance the density perturbation, giving rise to instability.

In both cases the phase fronts of the waves are very closely field-aligned because the component of ionospheric current parallel to the geomagnetic field is too weak to drive any instability. Linear theory predicts that, in either case, waves travelling in a given direction will have a phase velocity approximately equal to the component of electron drift velocity in that direction. However, non-linear effects may limit the wave growth, cause secondary waves to propagate in directions that are not linearly unstable, and cascade waves to shorter wavelengths (Sudan et al., 1973; Greenwald, 1974).

The properties of the irregularities allow us to gain knowledge of the E region plasma dynamics from an analysis of a backscattered radar signal. The transmitted wave is backscattered by Bragg reflection from the electron density irregularity wavefronts. By conservation of momentum the backscatter is from irregularities with a wavelength equal to one half of the radar wavelength and is Doppler shifted due to the phase velocity of the irregularities. The reflection off wavefronts allows a phase coherent integration of the backscattered signal such that the received power is considerably in excess of that using incoherent scatter. In the latter case backscattered power is proportional to the electron density, whereas for coherent scatter the power is proportional to the square of the electron density.

The received power is a product of the radar gain/loss characteristics and the ionospheric backscatter cross-section (e.g. Farley et al., 1981). The former is known for a given radar, and thus the residual variations in the radar backscatter can be attributed to ionospheric effects. The backscatter cross-section can be written as

$$\sigma = N^2 (\Delta N/N)^2 F(\alpha, \beta) \quad (5.1)$$

where N is the mean electron density in the scattering region, $(\Delta N/N)^2$ is the mean square relative electron density fluctuations, and $F(\alpha, \beta)$ is a function of the radar aspect angle, α , and flow angle, β (Waldock et al., 1985). The field-aligned nature of the irregularities means that for aspect angles away from orthogonality with the field the return signal is strongly attenuated by typically 8 dB/deg (e.g. Ecklund et al., 1975). Linear theory predicts that plasma will be unstable to the two-stream instability for an electron drift speed, v_e , in excess of the plasma acoustic speed, c_s , only within a cone of half-angle $\cos^{-1}(c_s/v_e)$. Inside this cone the backscatter maximises in the direction of the electron drift and is attenuated by typically 0.45 dB/deg away from it (Haldoupis and Nielsen, 1984). For $v_e < c_s$ only gradient drift waves should be present and their propagation direction depends on the prevailing density gradients. In practice, VHF radar backscatter generally shows a clear threshold corresponding to an auroral electric field of $\sim 15 \text{ mV m}^{-1}$. This is close to the threshold for the two-stream instability predicted by linear theory and thus indicates that the gradient drift instability is unlikely to be the dominant mechanism for radar backscatter. The backscatter is found to be co-located with the electrojet (Greenwald et al., 1975) and to correlate positively with magnetic activity with no evidence of non-linear saturation at high K_p (Waldock et al., 1985).

We now consider the Doppler shift of the backscattered signal and the relationship of the irregularity motion to the $\mathbf{E} \times \mathbf{B}$ drift. The SABRE system does not measure a backscatter spectrum, but instead calculates the signal strength and Doppler shift by a single pulse - double pulse transmission sequence. The pulse width is 100 μs and the backscattered signal is sampled at 50 times (ranges) with this resolution (30 km) after a short lag (3.4 ms) corresponding to the nearest range gate.

The backscattered power from a range j is given by

$$P(j) = A^2(j) + B^2(j) \quad (5.2)$$

where $A(j)$ and $B(j)$ are the quadrature outputs at the appropriate time lag, averaged over the chosen integration period (20 s). The background noise level at this range is also measured by a single sampling in an interval between the single- and double-pulse samples.

The Doppler velocity at a given range, j , is found by calculating the double pulse autocorrelation coefficient whose real and imaginary parts are, respectively, $R(j)$ and $I(j)$, given by

$$R(j) = A(j) A(j+n) + B(j) B(j+n) \quad (5.3)$$

$$I(j) = A(j+n) B(j) - A(j) B(j+n) \quad (5.4)$$

where n is the double pulse separation ($300 \mu\text{s}$) in units of the sampling resolution ($100 \mu\text{s}$) i.e. $n = 3$. The average Doppler shift over the integration period is then given by

$$\Phi(j) = \tan^{-1} \{I(j)/R(j)\} \quad (5.5)$$

from which may be found the Doppler velocity of the irregularities at this range.

There are two important assumptions that are made in the calculation of the irregularity drift. These relate to the uniformity in space and time of the irregularity drift velocity. In order that the values of the Doppler shift measured by the above technique are unbiased estimates of the irregularity drift then it is essential that the propagation direction of the waves is uniform over the radar range cell (30 km) and that the wave phase speed is constant over the integration time (20 s). Furthermore, in order for the autocorrelation to work at all, the irregularities must exist for longer than the double pulse separation ($300 \mu\text{s}$).

If the above conditions are valid then linear theory tells us that the irregularity drift velocity derived from the measured Doppler shift is equal to the component of the electron drift velocity in the ion rest frame, and hence a very good estimate of the $\mathbf{E} \times \mathbf{B}$ drift velocity. However, in the equatorial electrojet this is not the case. Instead the two-stream irregularities always appear to propagate at the ion acoustic speed in the direction of the electron drift velocity (Cohen and Bowles, 1963; Bowles et al., 1963). Similar behaviour has also been observed with UHF radars in the auroral zone (e.g. Abel and Newell, 1969). When making a scan in azimuth the measured Doppler velocity was found to be approximately constant with azimuthal angle for azimuthal angles greater than $\sim 20^\circ$. In a transition region about the meridian (half width 20°) the Doppler velocity changed rapidly from the velocity "plateau" of one polarity to the other. The apparent saturation of the irregularity drift at the ion acoustic speed indicates that non-linear processes are important in understanding the irregularity generation.

However, more recent measurements with VHF radars have shown that the instability behaviour in the auroral electrojet is very different to that at the equator. In particular, frequent measurements have been made of large Doppler velocities up to 2 km s^{-1} , well in excess of the typical ion acoustic speed (e.g. Greenwald and Ecklund, 1975). The expect-

tation that these motions are equal to the electron drift, in accordance with linear theory, was supported by comparisons of the irregularity velocities with F region plasma drifts which showed very good agreement (Ecklund et al., 1977), and by azimuthal scans which showed no obvious velocity plateau or sharp transition region (Greenwald et al., 1978). However, other studies have indicated that a coherent radar may progressively underestimate higher drift speeds above $\sim 600 \text{ m s}^{-1}$ (Nielsen and Schlegel, 1983). This dichotomy can be explained by the dependence on the electric field of the ion and electron temperatures and hence the ion acoustic speed (Schlegel and St.-Maurice, 1981). It is found that the measured Doppler velocities of the irregularities are effectively limited to the ion acoustic velocity, but that the latter increases in a parabolic manner with the electron flow speed (Nielsen and Schlegel, 1985). Thus the measured Doppler speed increases monotonically with increasing electron drift speed, but is not exactly equal to it. Nielsen and Schlegel found that the measured Doppler speed of the irregularities departs significantly from the actual line of sight electron drift speed when the latter is in excess of $\sim 700 \text{ m s}^{-1}$. Theoretical studies also support this view (Robinson, 1986). The results of Nielsen and Schlegel show that in any event the calculated flow direction is apparently well predicted. Most importantly for this study, however, is the fact that for reasonable ranges of the electron drift speed the relationship between the drift speed and the measured Doppler speed is approximately linear. Thus, in this approximation, electron drift velocity gradients in time and space are preserved in the measured Doppler velocity, but their absolute magnitude may be underestimated. We consider other possible sources of error to the estimation of the electron drift speed and its gradient in a later section.

We now consider how the bistatic nature of the SABRE radar facility allows the measurement of a two dimensional velocity field. The two radar sites are shown in Fig. 5.1. Each radar comprises 16 directional antennae with a half-power beamwidth of 3.2° and a beam separation of 3.6° , though only the central eight beams are used and these are shown in Fig. 5.1. The radars thus view a common area of the ionosphere of approximate dimension $500 \text{ km} \times 500 \text{ km}$. As mentioned earlier, the radar samples along each beam at 50 ranges separated by 30 km. Measurements are taken essentially simultaneously at all ranges on all eight beams and temporally averaged over an integration period of 20 s. The line of sight velocity measured within a given radar range cell is then combined with the line of sight velocity from the other radar that comes from the same ionospheric volume to calculate the horizontal irregularity velocity vector in that region. The resultant, discretely sampled, velocity field is mapped onto a geographic coordinate system covering the area 63.6°N to 68.6°N and -0.5°E to 12.0°E . Fig. 5.2 shows an example of electron drift velocity vectors inferred from the SABRE. A vector is plotted wherever the two radars view a common ionospheric volume and where the backscatter signal power at both stations is above a set threshold. Empirically it seems that the scattering instability occurs

only when the electric field magnitude is more than $\sim 15 \text{ mV m}^{-1}$, there is a natural cut-off in the backscatter power when the electron drift velocity is below $\sim 300 \text{ m s}^{-1}$. In the figure backscatter is above threshold at nearly all common viewing sites, so that the plotted vectors delineate the maximum possible viewing area of the SABRE shown earlier in Fig. 5.1. The viewing area is diamond shaped within the larger square on which the axes lie. There are about 350 independent velocity measurements in this snapshot with a spatial separation of 20 km. We remember that each measurement in fact represents the electron drift velocity averaged over the range cell area and over the integration time. The electron drift field is stored on magnetic tape as a spatial array of geographic North-South and East-West velocity components for each integration period.

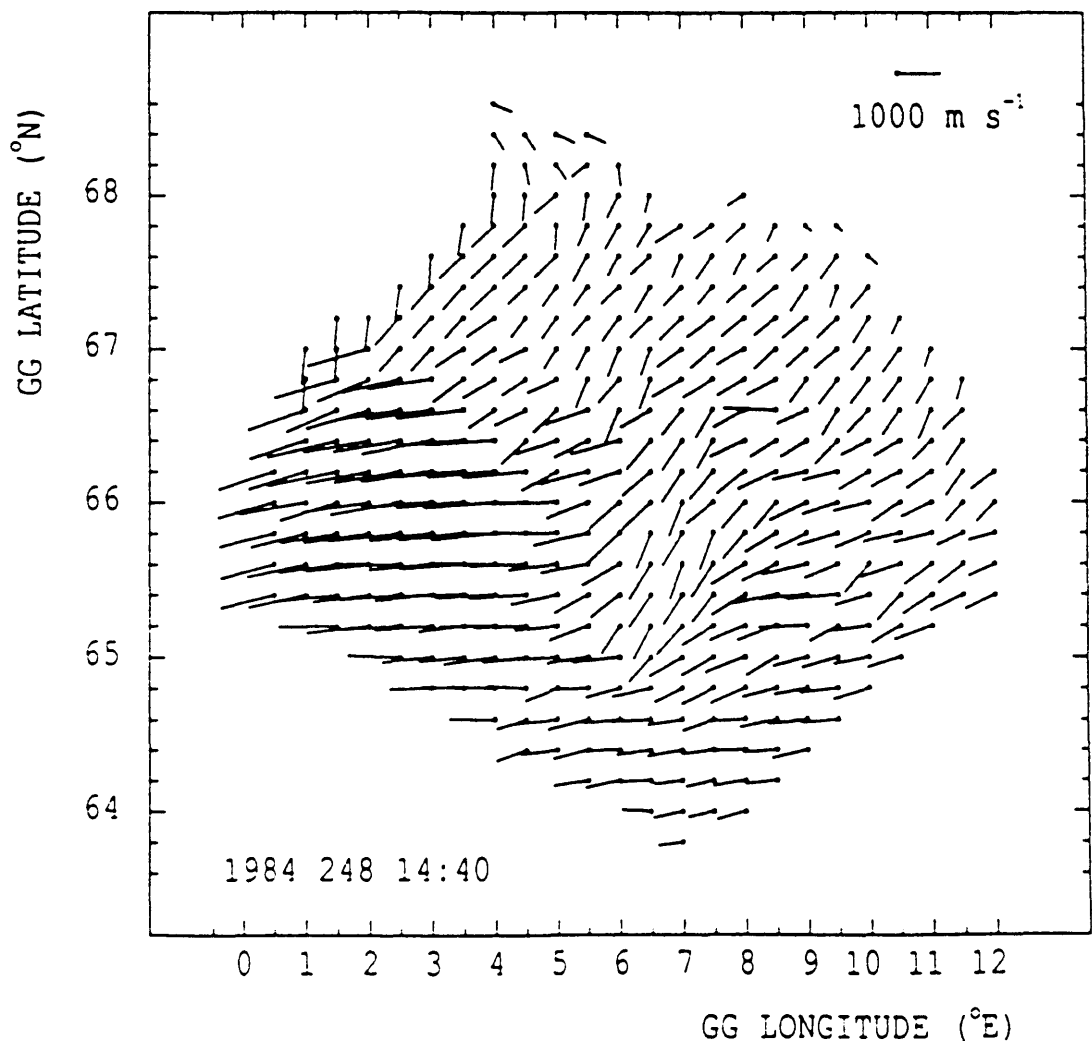


Fig. 5.2. A "snapshot" of the ionospheric electron drift velocity field at 14:40 UT over the SABRE field of view.

5.3. Analysis Technique.

We shall assume, *a priori*, that the inferred velocity field is the true electron drift velocity field. By looking at quantities that we expect to be conserved we might then be able to identify, *a posteriori*, regimes where the assumptions used in the measurement process are invalid. We find that one quantity that we expect to be conserved in the steady state is $\text{div } \mathbf{v}_e$, the divergence of the electron drift velocity field. We also identify a quantity, involving the measured electron drift velocity, which is a direct measure of a magnetospheric physical parameter that we wish to observe. We find that in the steady state the quantity $\text{curl } \mathbf{v}_e$, the curl of the electron drift velocity field, is directly proportional to the field-aligned current. We can therefore use this quantity to remotely sense and understand the physics of the magnetospheric region.

The electron-neutral collisional frequency is negligible in the E-region ionosphere and so magnetic field lines are "frozen in" to the electron flow:

$$\mathbf{E} = - \mathbf{v}_e \times \mathbf{B} \quad (5.6)$$

We shall assume that in the absence of an electric field the Earth's magnetic field is purely dipolar and shall also ignore the inclination of the field to the vertical. When an electric field is imposed the magnetic field is perturbed:

$$\mathbf{B} = \mathbf{B}_0 + \mathbf{b} \quad (5.7)$$

Thus $\mathbf{E}$, $\mathbf{v}_e$, and $\mathbf{b}$ are first order terms with respect to $\mathbf{B}_0$.

5.3.1. The divergence field.

Resolving the curl of equation (5.6) along the magnetic field we have:

$$\begin{aligned} \mathbf{B} \cdot \text{curl } \mathbf{E} &= \mathbf{B} \cdot \text{curl } (\mathbf{B} \times \mathbf{v}_e) \\ &= \mathbf{B}^2 \text{div } \mathbf{v}_e - \mathbf{B} \cdot \mathbf{v}_e \text{div } \mathbf{B} \\ &= \mathbf{B}^2 \text{div } \mathbf{v}_e \end{aligned} \quad (5.8)$$

In steady state, $\text{curl } \mathbf{E} = 0$, and thus the electron motion is incompressible.

When the derived value of $\text{div } \mathbf{v}_e$ is non-zero then we might expect it to be due to one of two possible causes. Firstly, the steady state approximation may no longer be valid. However, the ionosphere remains essentially incompressible even under time-dependent conditions because of the large ambient geomagnetic field; an order of magnitude argument shows that fluctuations in the magnetic field of order 1000 nT on time scales of 1 min

generate divergences of less than 1 mHz. Alternatively, the electron drift velocity or its gradient inferred from the backscattered signals may be in error, as we discuss later.

5.3.2. The vorticity field.

Taking the divergence of the frozen-in field condition given by equation (5.6) yields:

$$\mathbf{B} \cdot (\text{curl } \mathbf{v}_e) = -\text{div } \mathbf{E} + \mathbf{v}_e \cdot (\text{curl } \mathbf{B}) \quad (5.9)$$

Substituting for $\mathbf{B}$ using equation (5.7) and neglecting terms of second order or higher, equation (5.9) simplifies to:

$$\text{div } \mathbf{E} = -\mathbf{B}_0 \cdot (\text{curl } \mathbf{v}_e) \quad (5.10)$$

By definition, $\text{curl } \mathbf{B}_0 = 0$.

If the Pedersen conductivity is locally uniform in the ionosphere then:

$$j_{\text{par}} = \text{div } \mathbf{I} = -\Sigma_P \mathbf{B}_0 \cdot (\text{curl } \mathbf{v}_e) \quad (5.11)$$

where $\mathbf{I}$ and Σ_P are the height integrated Pedersen current density and conductivity respectively, and j_{par} is the field aligned current density. If the vorticity is calculated by a difference equation using discrete velocity measurements on a spatial grid, then equation (5.11) relates the vorticity to the local field-aligned current density if the Pedersen conductivity varies on a length scale much longer than the distance between neighbouring grid points (~ 20 km). In the absence of any field aligned current source within the field of view we expect the vorticity field to be given by the lower order terms. Putting $\text{div } \mathbf{E} = 0$ in equation (5.9) yields:

$$\begin{aligned} \mathbf{B} \cdot (\text{curl } \mathbf{v}_e) &= \mathbf{v}_e \cdot (\text{curl } \mathbf{B}) \\ &= \mu_0 \mathbf{v}_e \cdot (\mathbf{j}_P + \mathbf{j}_H) = -\mu_0 \mathbf{v}_e \cdot \mathbf{j}_H \end{aligned} \quad (5.12)$$

where $\mathbf{j}_P$ and $\mathbf{j}_H$ are the Pedersen and Hall current densities respectively, and μ_0 is the permeability of free space. Writing $\mathbf{j}_H = \sigma_H \mathbf{E} = \sigma_H \mathbf{v}_e \times \mathbf{B}$, we have:

$$(\text{curl } \mathbf{v}_e)_{\text{par}} = \mu_0 \sigma_H v_e^2 \quad (5.13)$$

Thus for an electron drift speed of 500 m s^{-1} and a typical Hall conductivity ($\sim 10^{-4}$ Siemens) we find that the expected value of the vorticity in the absence of local field aligned currents is ~ 0.03 mHz. Values of the vorticity in excess of this figure can arise from one of two sources. Firstly, as indicated above, it may be due to a source of field aligned current at this point. The structure of the current sheet could be seen over several neighbouring data points if it is of dimensions greater than the range cell. Alternatively, vorticity

values above 0.03 mHz could arise from errors in the inferred electron drift velocity or its gradient.

5.4. Method for the Evaluation of the Divergence and Vorticity Fields.

The spatially discrete nature of the data means that we have to rewrite the expressions used to calculate quantities such as the divergence and vorticity as difference equations.

To find the divergence or curl of some vector we need to know the spatial partial derivatives of its components. To estimate these derivatives using discrete data we first consider the Taylor expansion of a scalar quantity, f , which is known at a point $(x \pm a)$, where a is a small displacement from the position, x , at which the value of the spatial derivative is to be found:

$$f(x + a) = f(x) + f'(x) \cdot a + 1/2 f''(x) \cdot a^2 + \dots \quad (5.14)$$

where the dash (') indicates the spatial derivative operator, d/dx .

Now from equation (5.14) we can see that an expression for the spatial derivative, $f'(x)$, can be obtained:

$$f'(x) = \{f(x+a) - f(x-a)\}/2a + O(a^2) \quad (5.15)$$

This expression is accurate to second order in a .

The result is generalised to two dimensions by replacing the total derivative by the appropriate partial derivative. Consider a grid where Δn and Δe are the distances between neighbouring data points in the geographic northward and eastward directions respectively. Let $n \cdot \Delta n$ and $e \cdot \Delta e$ be the north and east coordinates of a point within the field of view (n, e integer). Then the expressions for curl v_e and div v_e to second order are:

$$\text{curl } v_e = \{v_N(n, e+1) - v_N(n, e-1)\} / 2\Delta e - \{v_E(n+1, e) - v_E(n-1, e)\} / 2\Delta n \quad (5.16)$$

$$\text{div } v_e = \{v_N(n+1, e) - v_N(n-1, e)\} / 2\Delta n + \{v_E(n, e+1) - v_E(n, e-1)\} / 2\Delta e \quad (5.17)$$

where v_N and v_E are the northward and eastward components of the electron drift velocity. $v_N(n+1, e)$ is the northward flow component at position $((n+1) \cdot \Delta n, e \cdot \Delta e)$.

Thus to calculate the divergence or vorticity at a given point we use data from the four nearest neighbours. To minimise errors arising from this technique we check that all of the data points used have a backscatter power above a set threshold.

5.5. Sources of Error.

Before we employ the analysis technique to some real data, we first consider the limitations of the measurement method. We find the sources of error in the calculation of the divergence and vorticity fields to be threefold. Firstly, the measured Doppler velocity of the irregularities can, at times, depart from the actual line of sight electron drift velocity (Robinson, 1986). The effect is thought to lead to systematic under-estimates of flows in excess of $\sim 1 \text{ km s}^{-1}$, as mentioned earlier. Secondly, the finite integration time for the complete velocity field measurement may lead to inaccuracies during intervals of highly time-varying flow. Thirdly, when the spatial scale of a flow shear is comparable to the grid scale for the measurements, the discretisation can lead to erroneous relative weightings of the individual velocity measurements used to calculate the differential fields. To illustrate the effects of these errors on our analysis of the flow field we consider the anomalous perturbations that they cause in some property of the flow that we would otherwise expect to be conserved at all times. As we argued above the essential incompressibility of the geomagnetic field means that we expect the flow to be always divergence-free to a very good approximation. Thus by understanding the perturbations to the flow divergence field caused by the measurement errors, we can use the divergence field as a diagnostic of the accuracy of the measured velocity field and other quantities derived from it.

Let us first consider the perturbations to the divergence field which may result from a non-linear saturation of the irregularity drift velocity and hence a progressive under-estimation of the true $\mathbf{E} \times \mathbf{B}$ drift. For simplicity we shall assume that the primary effect on the measured velocity is an underestimation of the velocity magnitude, but that the flow direction is accurate (Nielsen and Schlegel, 1985). Thus we may define some function, $\alpha = \alpha(v)$, that relates the measured flow speed, $v_m(x,y)$, to the true flow speed, $v(x,y)$. Let us take this function to be

$$\alpha(v) = (v_0/v) \sinh^{-1}(v/v_0) \quad (5.18)$$

which has the property that at a plasma drift speed of v_0 the measured flow speed is an underestimate by 12%, and that the underestimation increases with increasing flow speed. From our earlier discussion we expect the value of v_0 to be about $0.5\text{-}1 \text{ km s}^{-1}$. If we now calculate the measured flow divergence field taking account of saturation effects we have

$$\begin{aligned} \nabla \cdot \mathbf{v}_m &= \alpha(v) \nabla \cdot \mathbf{v} + \mathbf{v} \cdot \nabla \alpha \\ &= \mathbf{v} \cdot \nabla \alpha(v) \end{aligned} \quad (5.19)$$

for an incompressible fluid. Thus we find that if there exists a gradient of the saturation factor, α , along the background flow direction then an erroneous non-zero divergence will

be measured. Note that if the fluid flows in a direction orthogonal to the gradient of its magnitude then the measured divergence is always zero. An example of this situation would be an azimuthally gyrating incompressible fluid. Alternatively, if the fluid streams in one direction with no velocity gradients i.e. laminar flow, then the divergence field would again be zero, regardless of the flow speed and the amount of saturation. But in the general case the error in the divergence field depends principally on the velocity, and hence saturation, gradients in the flow. As an illustration consider a simple incompressible flow field described by $\mathbf{v} = (mx, -my)$ i.e. a hyperbolic-like flow jet. We find that in this case the measured divergence field is given by

$$\nabla \cdot \mathbf{v}_m = m(x^2 - y^2) (v_0/v)^2 \{ (v^2 + v_0^2)^{-1/2} - v^{-1} \sinh^{-1}(v/v_0) \} \quad (5.20)$$

This will maximise, for given radial distance from the origin (given v) along the x and y axes. Putting $y = 0$ we find the peak divergence at a flow speed near $3v_0$ with a magnitude of $\sim 0.2 m$. The largest flow shears seen in the E region ionosphere are probably about 1 km s^{-1} over 100 km, which gives $m = 0.01$. Thus by this simple argument the peak error in the measured divergence field due to instability saturation is estimated to be about 2 mHz.

Another source of error can arise during intervals of time-varying flow. Earlier we remarked that the SABRE radar averages the double pulse backscatter samples over an integration period of 20 s to minimise the random scatter of the measured Doppler shifts. However, if the flow varies in a systematic manner over this interval the derived velocity vector will be biased such that it is unlikely that the resultant velocity field is an accurate representation of the true velocity field present at any instant during the integration period. Instead it will be distorted such that the divergence field is no longer zero everywhere. An estimate of the magnitude of this effect is gained by considering the possible systematic error in the measurement of the time-varying flow and the scale length between neighbouring erroneous measurements. A minimum estimate for the latter is 20 km, the spatial resolution of the radar. We will see later that flow oscillations of $\sim 1 \text{ km s}^{-1}$ peak-to-peak amplitude and 2 min period can be excited within the E region ionosphere. Under these conditions the systematic error in the measured velocity is $\sim 200 \text{ m s}^{-1}$. Thus the likely error in the flow divergence field during these extreme time-varying conditions is $\sim 10 \text{ mHz}$.

Finally we consider the effect of the discrete nature of the radar measurements upon the differential vector quantities. In the above estimate of the time-dependent flow error we recognised that the effect of the spatial resolution of the radar is to create a high frequency cut-off in the spatial frequency spectrum of the velocity field. Thus any gradients within

the flow with scale lengths comparable to, or less than, the spatial resolution are effectively smoothed by the radar measurements.

The effect of the discretisation has been modelled, both analytically and numerically, using idealised flow fields. Firstly we consider the simple analytical case of a hyperbolic flow jet used above i.e. $\mathbf{v} = (mx, -my)$. When calculated on a lattice of spacing, Δ , the coordinates become, $x = i\Delta$, $y = j\Delta$, where i, j are integers. Using the discretised forms of the vector differentials given by equations (5.16) and (5.17) above it is simple to calculate that, in this case, the divergence and curl are both equal to zero, their analytical values, independent of the lattice spacing, Δ . The reason for this result lies in the fact that the partial derivatives of the flow field are not a function of position and hence the effectively linear interpolation performed by the central difference method of discretisation does in fact accurately describe the flow field below the spatial resolution of the measurements. However, if we consider the slightly more complex case of an azimuthally gyrating fluid given by $\mathbf{v} = (x^2 + y^2)^{1/2} (my, -mx)$, then the effect of discretisation becomes apparent. Analytically this flow field is divergence free, but has a curl that is linearly dependent on the distance, r , from the origin i.e. $\text{curl } \mathbf{v} = 3mr$. The non-constant flow gradients mean that the discrete measurements offer only limited knowledge of the flow field and information is lost at the highest spatial frequencies. Thus we find that the measured flow field yields a finite divergence and an erroneous vorticity. The calculated divergence and vorticity fields resulting from this velocity field, accurately measured but discretely sampled, are shown in Fig. 5.3a and Fig. 5.3b respectively. The grid is of dimensions $25 \Delta \times 25 \Delta$, representative of the SABRE measurement lattice. The contours connect values of constant divergence/vorticity, with solid (dashed) contours representing negative (positive) values, and the maximum and minimum values (in arbitrary units) shown at the top of the figure. It can be seen that the measured divergence is only a small fraction of the peak vorticity. The error in the vorticity field is similarly small.

Recognising that the errors due to discretisation arise from a high spatial frequency cut-off, we now model the case of a step-like shear in the flow field at arbitrary orientation to the measurement lattice. The velocity field is ensured to be divergence free by imposing, on either side of the shear boundary, a uniform flow that is directed parallel to it. Mathematically, for a given position (x, y) , if $y > \beta x$ then $\mathbf{v} = (1 + \beta^2)^{-1/2} (v_0, v_0 \beta)$, or if $y < \beta x$ then $\mathbf{v} = -(1 + \beta^2)^{-1/2} (v_0, v_0 \beta)$. In Fig. 5.4a(b) and Fig. 5.4c(d) we present the calculated divergence (vorticity) fields, in the same format as in Fig. 5.3, for the flow shear described above orientated at 45° ($\beta = 1$) and $\sim 27^\circ$ ($\beta = 0.5$) to the i axis respectively. In both cases a linear plateau of high vorticity can be seen, with a width of about one range cell. The peak vorticity magnitude is less than the infinite value associated with the discontinuous shear in the analytical velocity field. The value is smaller for the shear inclined

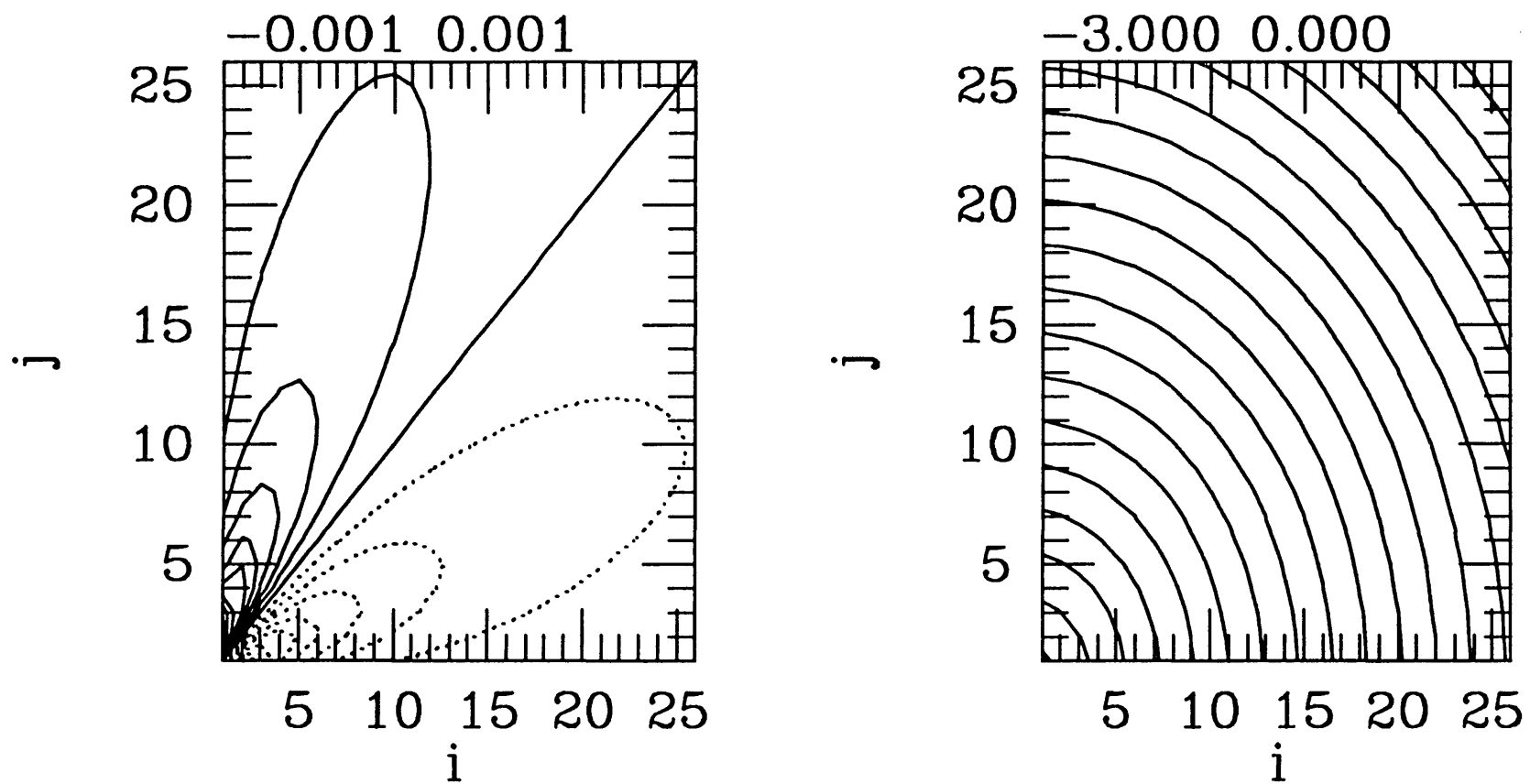
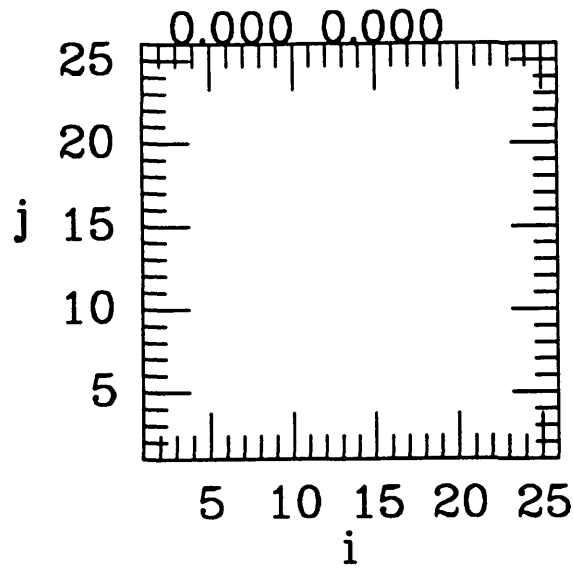


Fig. 5.3. The divergence (a) and vorticity (b) fields of an azimuthally gyrating fluid, calculated using discretised measurements of the velocity field (see text).

(a)



(b)

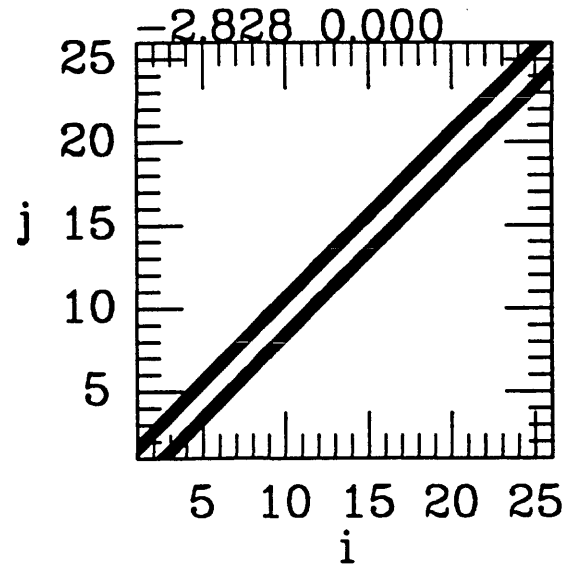
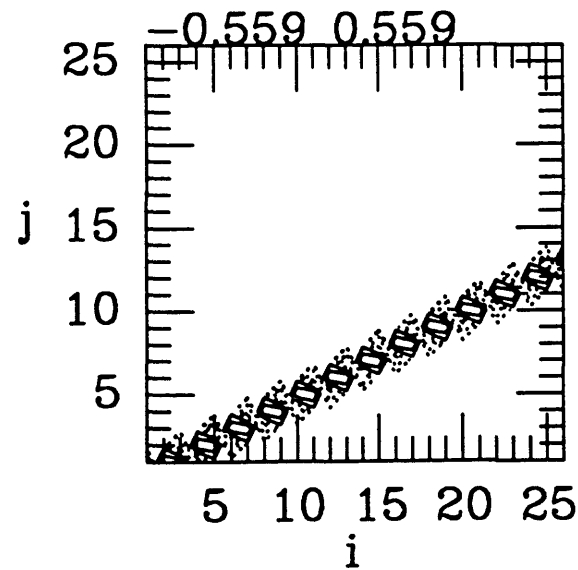


Fig. 5.4. The divergence (a) and vorticity (b) fields across a discontinuous flow shear calculated from discretised measurements of the velocity field (see text). The flow shear is orientated at 45° to the x (i) axis of the measurement lattice.

(a)



(b)

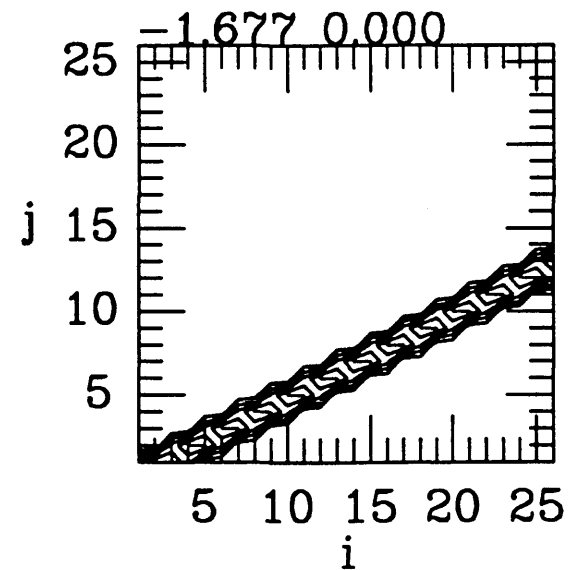


Fig. 5.4. The divergence (c) and vorticity (d) fields across a discontinuous flow shear calculated from discretised measurements of the velocity field (see text). The flow shear is orientated at $\sim 27^\circ$ to the x (i) axis of the measurement lattice.

at 27° than for the 45° case, and the shear region is slightly broader in the 27° case. The reason for the variable shear width and vorticity strength is simple. The calculated vorticity falls to zero away from the boundary when all four of its "nearest neighbours" have the same flow vector. The distance that this point lies from the shear boundary in a direction normal to it is proportional to the cosine of the smallest angle of inclination of the shear to a lattice axis. This width effectively defines the length scale of the velocity shear gradient. Since the magnitude of the flow on either side of the shear boundary is held constant in our examples, the peak magnitude of the vorticity is limited by the spatial resolution of the measurements. For a shear with an imposed scale length of order the range cell distance (30 km) and $v_0 = 200 \text{ m s}^{-1}$, we would measure $\text{curl } \mathbf{v}_e \sim 14 \text{ mHz}$ ($\beta = 1$) and $\text{curl } \mathbf{v}_e \sim 8 \text{ mHz}$ ($\beta = 0.5$).

By a comparison of Fig. 5.4a and Fig. 5.4c it is apparent that the calculated divergence field is also affected by the discretised sampling of a discontinuous velocity shear. When the shear is aligned at 45° to the i axis the divergence field is divergence free, in agreement with the analytical result. However, in the 27° case non-zero divergences are measured with a magnitude that is a sizeable fraction ($\sim 33 \%$) of the peak measured vorticity. This corresponds to $\text{div } \mathbf{v}_e \sim 3 \text{ mHz}$ when the measured vorticity is $\sim 8 \text{ mHz}$, as in the example given above. The non-zero divergences are co-located with the vorticity plateau and oscillate in polarity along the shear boundary. The reason for this behaviour is that any point close to the sharp boundary will not sample the velocity field in an unbiased way. In the 45° case the nearest neighbours comprise equal contributions from each side of the shear, but this is not so in the 27° case. Clearly then the discrete nature of the measured velocity field can give rise to erroneous measurements due to the loss of information about the higher spatial frequencies present in the true velocity field. Additionally, we find that the orientation of flow gradients with respect to the measurement lattice is important.

In summary, all three sources of error identified at the beginning of this section could be significant. The largest error is likely to arise from the temporal averaging of the velocity measurements ($\sim 10 \text{ mHz}$ during extreme conditions). The maximum errors due to the spatial resolution of the measurement lattice and the deviation of the measured irregularity velocity from the $\mathbf{E} \times \mathbf{B}$ drift velocity are probably smaller ($\sim 2\text{-}3 \text{ mHz}$).

5.6. Results.

As an illustration of how the divergence and vorticity fields can be used as a diagnostic tool with SABRE we present some results from a case study on September 4, 1984. The event was studied in detail in Chapter 4 of which the key results were the following.

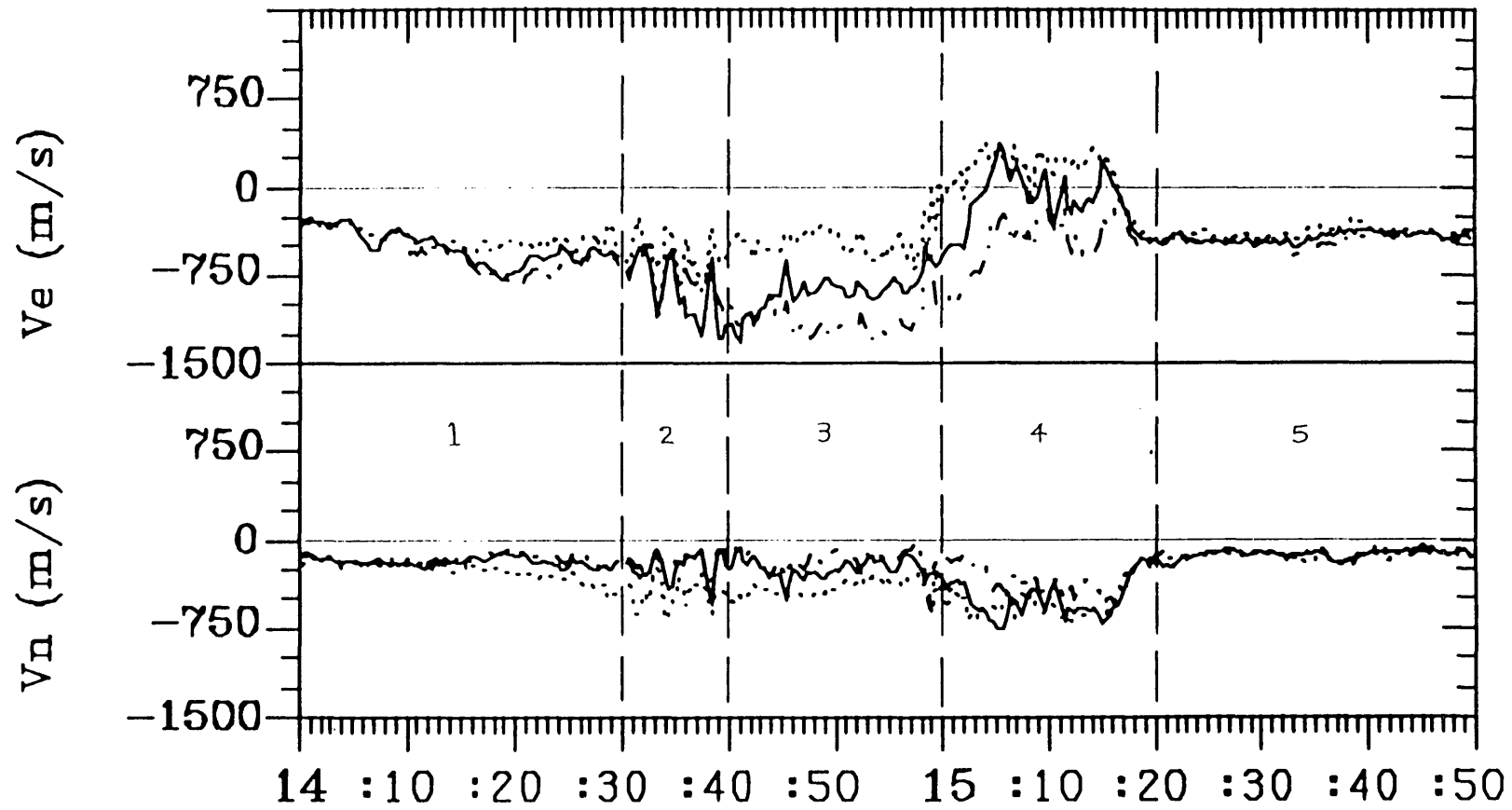


Fig. 5.5. The ionospheric electron drift velocity measured by SABRE versus Universal Time on September 4, 1984. The data are averaged over the longitudinal range 4-6 °E and over three 1° latitudinal ranges between 64.5 and 67.5 °N (geographic coordinates). Dashed line: 64.5 - 65.5 °N; solid line: 65.5 - 66.5 °N; dotted line: 66.5 - 67.5 °N.

AMPTE-IRM measurements from the magnetopause boundary layer showed that the dayside magnetosphere was undergoing erosion, at least from 14:42 UT to 15:01 UT. Concurrent measurements on the ground support this view by the observation of an expanding polar cap between $\sim 13:50$ UT and $\sim 15:00$ UT. By the end of this interval the polar cap boundary was thought to be just poleward of the SABRE field of view. An enhancement in the nightside reconnection rate was inferred from ground magnetometers to have occurred at $\sim 14:20$ UT and peaking at $\sim 15:00$ UT (see Fig. 4.16). Initially the enhancement was insufficient to arrest the polar cap growth, but the peak was large enough to drain flux from the polar cap which contracted poleward over the interval $\sim 15:00 - 15:40$ UT (see Fig. 4.15).

Fig. 5.5 summarises the variation of the SABRE electron drift velocity field over the universal time of interest near 16:00 MLT. The data have been averaged over three areas within the SABRE viewing area. Each area is approximately two degrees of longitude by one degree of latitude, centred on 5°E and 65.0 , 66.0 , and 67.0°N in geographic coordinates ($\text{MLT} \sim \text{UT} + 2 \text{ h}$, $L \sim 5$). The latitudinal bins are denoted by the different line types as indicated. The upper and lower panels show the geographic eastward and northward electron drift flow speeds, respectively (geographic North is $\sim 30^\circ$ clockwise of geomagnetic North; see Chapter 2). The time sequence has been divided into 5 intervals, indicated by the dashed vertical lines in the figure.

In intervals 1 and 5 the flows were similar in all three bins indicating laminar flow, and the flow magnitude was fairly steady. In interval 1 the equatorward component to the flow, increasing with latitude, is thought to be due to polar cap expansion (see Chapter 2). The divergence and vorticity fields at 14:15 UT in interval 1 are shown in Fig. 5.6. The fields are presented in the form of contour plots with the interval between contour levels set at 5 mHz. Positive values of the divergence and curl are denoted by a dashed linetype, negative values by a solid linetype. It can be seen that the values of both the divergence and vorticity were below 5 mHz almost everywhere. The divergence and vorticity fields during interval 5 (not shown) yield similarly low values. The low values of divergence were measured at times when the flow field was steady and demonstrate the incompressibility of the ionospheric electron plasma under such conditions. During these intervals there appeared to be no local field-aligned current sheet, as evidenced by the small value of vorticity everywhere within the field of view. There were, however, small regions where the values of the curl and divergence were significant. We note that these are generally of only one pixel in size, requiring only one of the four data points used in the calculations to be in error. The small dimensions of these features thus suggest that they arise due to erroneous measurements of the electron drift velocity at individual points. Their location at the northern edge of the field of view means that they use data from the furthest range gates

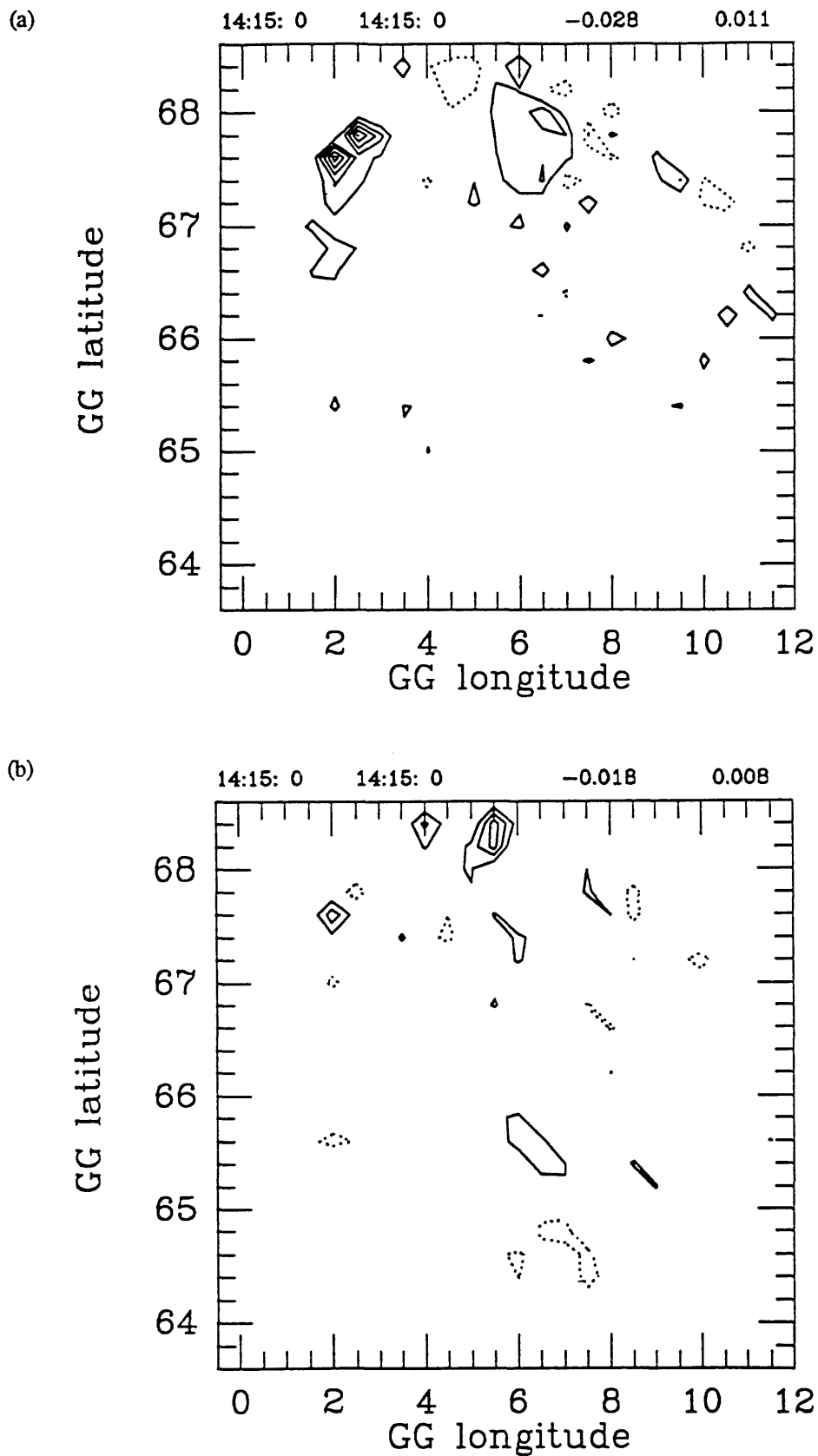


Fig. 5.6. The divergence (a) and vorticity (b) fields at 14:15 UT over the SABRE field of view, calculated using the discrete electron drift velocity measurements (see text).

of the radar beams. It may be that the radar measurement technique is unreliable at these outer limits.

Between 14:30 UT and 14:40 UT, in interval 2, the central and high latitude bins experienced large amplitude pulsations. Waldock et al. (1988) have examined the pulsations in detail and showed them to be intimately related to the concurrent rapid enhancement in the background flow and to have a westward phase motion of $\sim 8 \text{ km s}^{-1}$. The flow enhancement was observed earlier at $\sim 14:20$ UT by a ground station ~ 4 h anti-sunward of SABRE (not shown). This global westward phase motion of $\sim 5 \text{ km s}^{-1}$ is similar to the observed westward wave phase speed. We argue that the observations show the propagation to the dayside of an inferred enhancement in the tail reconnection rate. However, as mentioned above, the increase was insufficient to halt the prevailing polar cap expansion. During the pulsations, at 14:35 UT, the divergence and vorticity fields (Fig. 5.7a,b) were highly disturbed. The source of the large erroneous divergences is thought to be the temporal variability of the velocity field. The peak values of the derived vector differentials are closely co-located with the localised peak wave power (see Fig. 6, Waldock et al., 1988) and the magnitude of the peak divergence is comparable to our earlier error estimate of $\sim 10 \text{ mHz}$ due to such large temporal variation. In the vorticity field can be seen the beginnings of a current sheet that extends right across the field of view by interval 3.

At 14:50 UT, in interval 3, the flow components were again fairly steady, as in interval 1, but there existed a large latitudinal velocity gradient. The divergence and vorticity fields at this time are shown in Fig. 5.8a,b. The former is again very small with only isolated data points having a divergence above 5 mHz . The flow speeds at this time range from $\sim 600 \text{ m s}^{-1}$ in the highest latitude bin to in excess of 1200 m s^{-1} at low latitude. Even in these exceptional conditions the incompressible flow approximation holds good. The vorticity field however shows some very interesting features. The most striking is the long, linear plateau of high vorticity ($> 10 \text{ mHz}$). This we interpret as a field-aligned current sheet (cf. equation (5.11)). The feature persists over the whole of interval 3 (cf the sharp rotation of the flow at 14:40 UT in Fig. 5.2), unlike the smaller scale structures in the curl and divergence fields which come and go in a random manner. To assess whether the pixel sized regions of high divergence and curl were associated with random errors in the measurement technique, we have also temporally averaged the divergence and vorticity fields over a central 10 min section of interval 3. The divergence field (not shown) was indeed reduced further, whilst the vorticity sheet persisted. The source of the steady state current sheet we shall argue to be due to hot plasma effects in the magnetosphere, associated with the flow enhancement during interval 2, which severely modified the imposed electric field and hence the convection pattern.

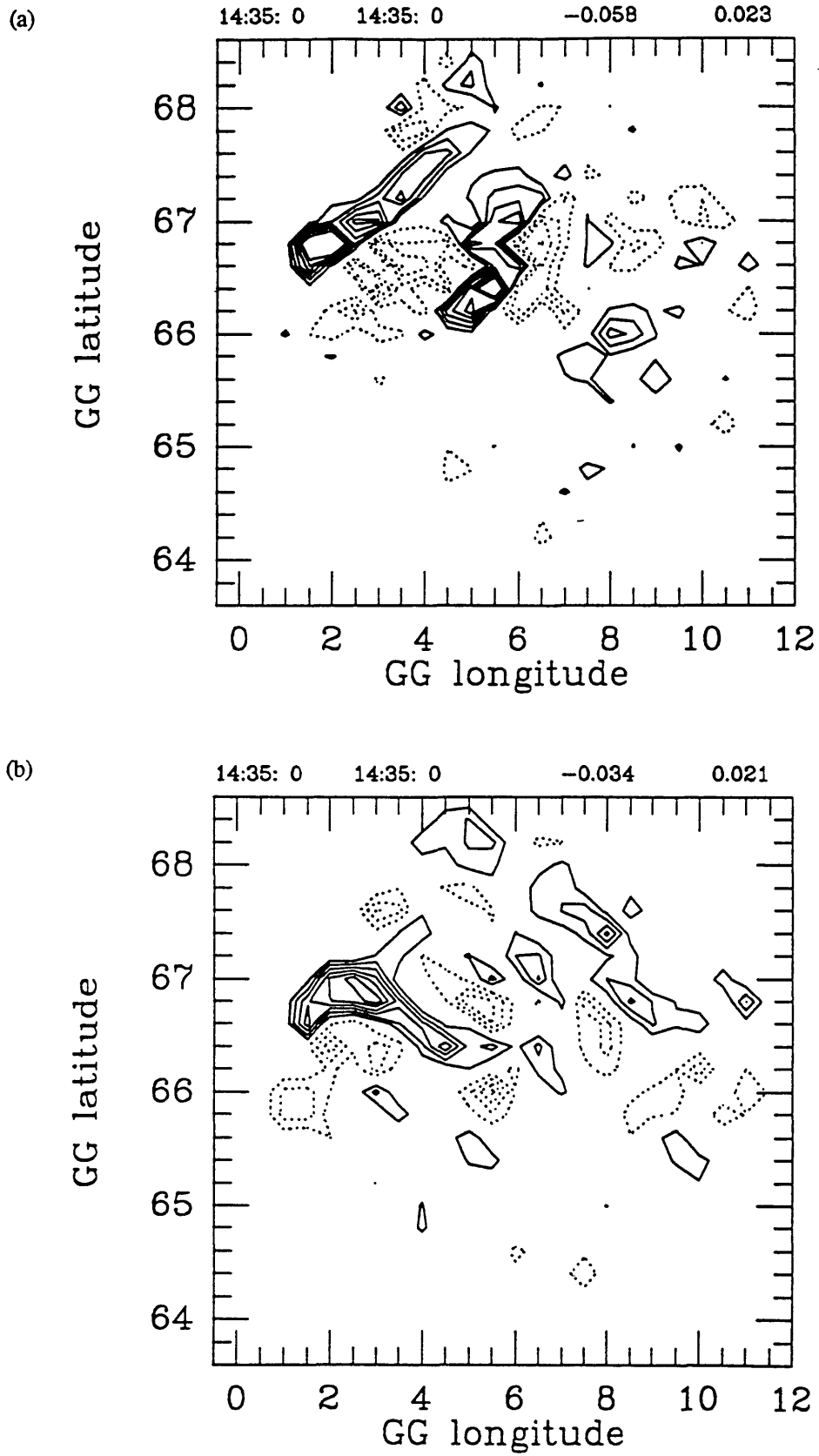


Fig. 5.7. The divergence (a) and vorticity (b) fields at 14:35 UT over the SABRE field of view, calculated using the discrete electron drift velocity measurements (see text).

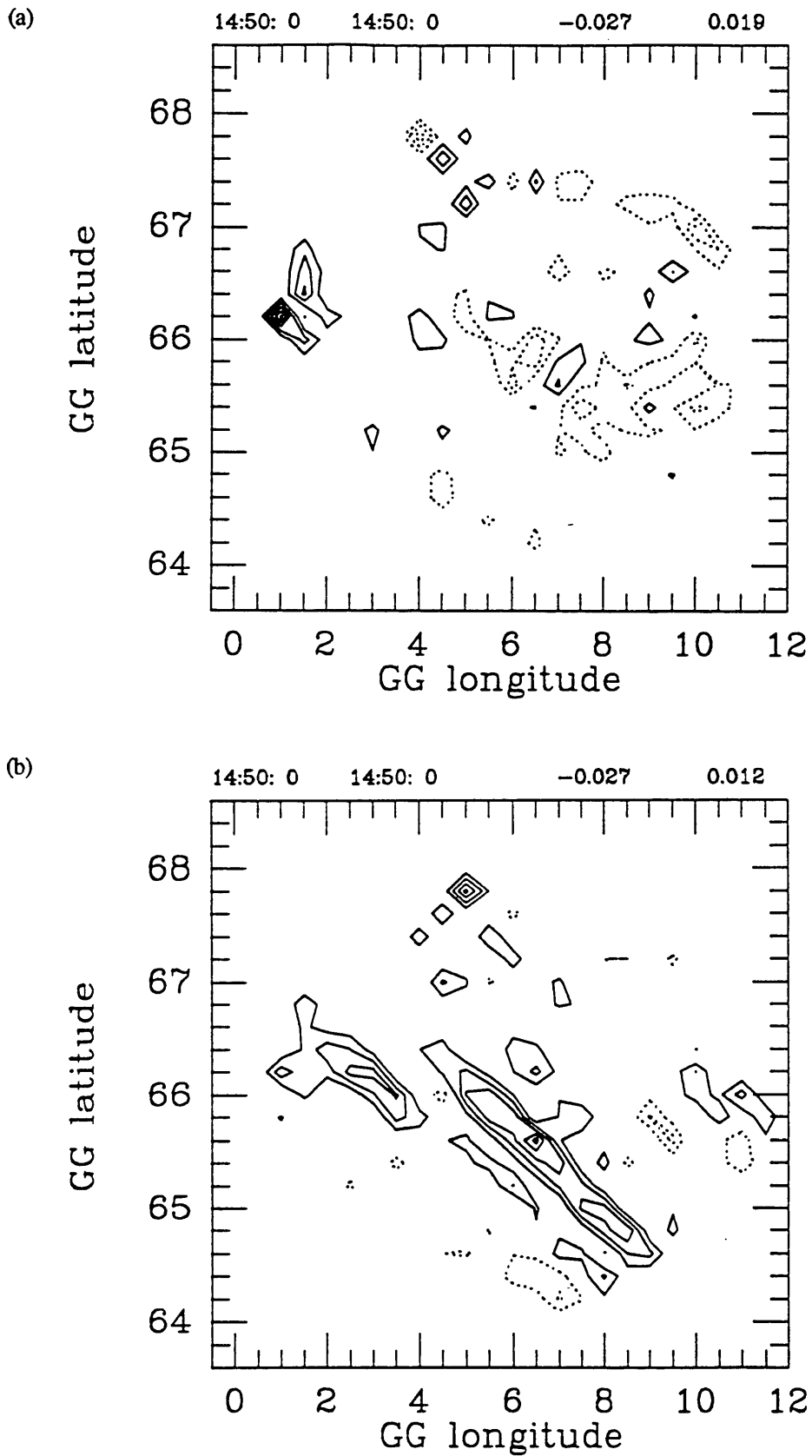


Fig. 5.8. The divergence (a) and vorticity (b) fields at 14:50 UT over the SABRE field of view, calculated using the discrete electron drift velocity measurements (see text).

The situation at 15:10 UT, in interval 4, was similar to that at 14:35 UT with large temporal variations in the flow. Large flow divergences were again measured and the vorticity field (not shown) gives evidence for the break-up of the current sheet that was present in interval 3, though the situation is highly complicated. The decay of the current sheet during interval 4 coincides with a rapid poleward contraction of the polar cap boundary.

5.7. Discussion and Conclusion.

In summary, we have investigated some properties of the ionospheric plasma by looking at quantities which we expect to be conserved ($\text{div } \mathbf{v}_e = 0$ in the steady state), or which are a direct measure of some interesting physical entity ($\text{curl } \mathbf{v}_e$ is directly proportional to the local field-aligned current).

Our expectation that the electron plasma is incompressible in the steady state has been supported by our analysis, even during a period of high electric field strength and strong velocity gradient. The measurement, using discrete data, of only small divergences in the presence of a strong, localised flow shear was probably aided by the orientation of the shear approximately along an axis of symmetry of the measurement lattice. The predicted effects of discretisation may be detectable in the oscillating polarity of the divergence along the vorticity plateau seen in Fig. 5.8. However, during intervals of highly time-varying flow, non-zero divergences were measured which were comparable in magnitude to the vorticity (~ 10 mHz), as might be expected from the earlier error analysis. Temporal averaging of the data tended to reduce the divergence, supporting its association with the time-dependent flow behaviour. Residual large divergences were also present at the furthest range cells of the two radars. The small spatial scale of these anomalies suggests that the noise level may be a problem for backscatter Doppler measurements at these distances.

We have shown the presence of a strong, large-scale vorticity of the electron flow following pulsation activity. Waldock et al. (1988) demonstrated a close correspondence of the pulsation behaviour to the vorticity sheet structure. Referring to equation (5.11), the sense and strength of the vorticity sheet implies the presence of a co-located upward field-aligned current of $\sim \text{few } \mu\text{A m}^{-2}$ across the SABRE field of view, unless there was a precisely matched change in the ionospheric conductivity across the sheet. Statistically, the conductivity distribution in the mid-afternoon sector of the auroral zone ionosphere, where this observation was made, is expected to be the most uniform (Wallis and Budzinski, 1981). However, due to the unusual geomagnetic conditions that prevailed during the event, we cannot be sure that conductivity gradients did not exist. Evidence that the vor-

ticity sheet is a current sheet of magnetospheric origin is provided by the observation that the sheet stands in the flow for ~ 20 min before its decay.

We shall now consider how such a current sheet might arise in the middle magnetosphere. Let us employ a simple fluid model where the plasma moves in the presence of electric and magnetic fields and the plasma pressure is isotropic. Now, neglecting inertia, the momentum equation can be written:

$$\mathbf{j} \times \mathbf{B} = \nabla p \quad (5.21)$$

Integrating along field lines this may be re-expressed in the form:

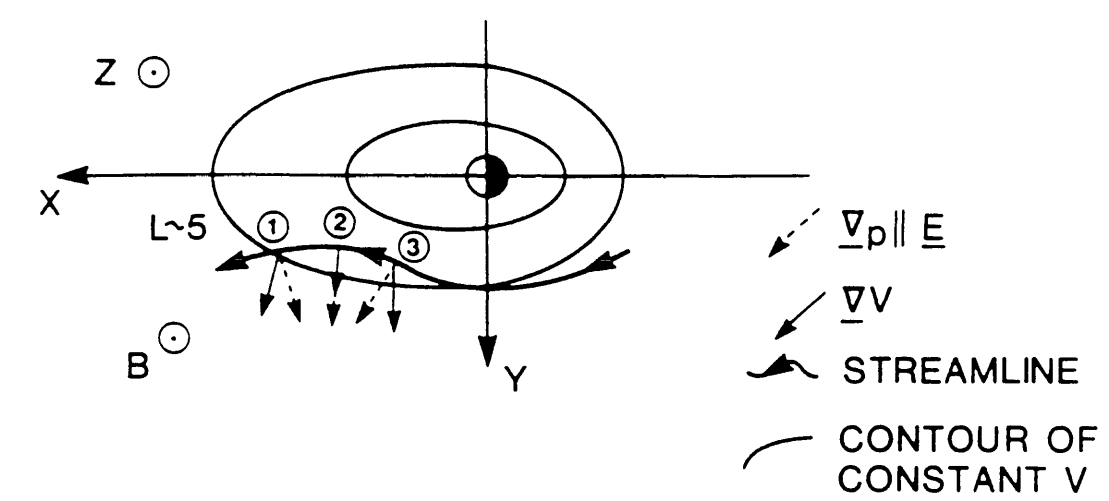
$$B_{eq}^2 \nabla \cdot \mathbf{I} = B_I \nabla p \cdot (\mathbf{B}_{eq} \times \nabla \mathbf{V}) \quad (5.22)$$

where $\mathbf{I}$ is the height-integrated ionospheric current, B_I and B_{eq} are the magnetic field strengths in the ionosphere and magnetospheric equatorial plane respectively, and $\mathbf{V}$ is the flux tube volume (Southwood, 1977).

We can now estimate from our observations the strength of the magnetospheric pressure gradient required to drive the measured field-aligned current. Using equation (5.11), which relates the calculated vorticity to the field-aligned current strength, we find that the latter is $\sim (5 \pm 1) \mu\text{A m}^{-2}$, assuming a Pedersen conductivity of 8 mho (Wallis and Budzinski, 1981). Taking a dipolar magnetospheric field in the low beta approximation, we can determine the magnetic field strength and flux tube volume gradient at the current source in the magnetospheric equatorial plane. Thus substituting these values into equation (5.22) we find that the azimuthal component of the pressure gradient in the magnetospheric region conjugate to the SABRE field of view is $\sim (1.7 \pm 0.3) \times 10^{-15} \text{ N m}^{-3}$.

Let us consider how this azimuthal pressure gradient can occur. In Fig. 5.9 we sketch a scenario showing a typical fluid streamline in the equatorial plane of the magnetosphere, arising from a high latitude boundary condition appropriate to magnetospheric erosion. In the late afternoon magnetosphere plasma is carried onto flux tubes of smaller volume distorting the ambient pressure gradient to give it a component along the flux tube volume contour. Thus, if the local pressure gradient is distorted from a generally radial (anti-radial) orientation, we expect a strong upward (downward) field-aligned current to be driven at the conjugate point in the ionosphere. The sense of this current depends upon the general direction of the ambient pressure gradient which typically would be anti-radial in the middle and outer magnetosphere, outside the steep radial gradient at the ring current inner edge. However, measurements of the particle pressure in the late afternoon magnetosphere just prior to the event studied here indicate that enhancements to the plasma pressure in the outer magnetosphere generated a weak radial pressure gradient outside the ring current

BIRKELAND CURRENT SYSTEMS ARISING FROM
MAGNETOSPHERIC EROSION



$$B_{EQ}^2 \frac{\nabla \cdot \underline{I}}{\underline{I}} = B_I \frac{\nabla p}{p} \cdot (\underline{B}_{EQ} \wedge \underline{\nabla V})$$

REGION	$\frac{\nabla \cdot \underline{I}}{\underline{I}}$	BIRKELAND CURRENT SENSE
①	<0	UPWARD
②	0	-
③	>0	DOWNWARD

⇒UPWARD BIRKELAND CURRENT AT ~1600 MLT, L~5

Fig. 5.9. The Birkeland current systems in the middle magnetosphere arising from magnetospheric erosion.

inner edge in a localised region at $L \sim (5.0 \pm 0.5) R_E$ (Lui et al., 1987), which is precisely the region covered by the SABRE field of view. In addition, Lui et al. show evidence that, though the pressure is not isotropic as we assumed in equation (5.21), the dominant contribution to the ring current is the pressure gradient effect, rather than the field curvature effect which involves the pressure anisotropy. Though the observed pressure gradient was of the appropriate sense, its magnitude was insufficient to drive the strong upward field-aligned current seen by SABRE.

However, we noted earlier that the current sheet developed in the SABRE field of view immediately following a flow enhancement due to increased nightside reconnection, but that the latter was initially of insufficient strength to halt the magnetospheric erosion. The hourly averaged ring current index, D_{ST}, also increased considerably across this time. We propose that the sudden increase in the nightside reconnection rate caused the injection of particles into the outer magnetosphere, enhancing the ring current and steepening the previously observed radial pressure gradient at $L \sim 5$.

Thus, during the interval when we observed the current sheet at SABRE, the radar was ideally located to image the current system of the same polarity arising from an equatorial motion of plasma due to the prevailing polar cap expansion and concomitant distortion of a strong localised radial pressure gradient. When magnetospheric erosion ceased after $\sim 15:00$ UT during the peak nightside activity the current system immediately decayed.

We conclude that the concept of flow vorticity and its measurement using ionospheric radars can be a useful tool in the identification of field-aligned current structure in the magnetosphere. In this study it has been successfully shown how field-aligned currents are generated by hot plasma effects which can modify the imposed convection pattern and prevent its penetration to low latitudes (Southwood, 1977). We encourage the further use of the technique in identifying other magnetospheric current systems e.g. in the cusp, where an analysis might shed further light on the nature of the solar - terrestrial coupling process.

CHAPTER 6

CONCLUSION.

6.1. Introduction.

The aim of this thesis has been to consider how the ionosphere is coupled to the magnetosphere and the solar wind, and hence to understand the time-dependent response of the magnetosphere-ionosphere system to external changes in the solar wind.

An important benchmark in assessing our understanding of the solar-terrestrial interaction is the ability to forecast. As in meteorological forecasting, only coordinated observations using space- and ground-based instruments at high temporal resolution (as has been achieved in past substorm studies) can give us the information necessary to fully understand and predict the magnetosphere-ionosphere response to time-varying solar wind conditions.

In this thesis we considered probably the two dominant solar wind effects upon the magnetosphere and ionosphere and examined them with the use of an extensive array of space- and ground-based instruments.

6.2. The Effect of Solar Wind Pressure on the Magnetosphere-Ionosphere System.

In Chapter 1 we discussed how the solar wind pressure, in particular its dynamic pressure, determines the gross shape of the magnetosphere. The average size and shape of the magnetosphere has been shown to vary in the expected manner with the dynamic pressure. In Chapter 3 we presented an event in which a simple model of the solar wind - magnetosphere interaction could predict the changing position and motion of the magnetospheric boundary due to time-varying solar wind pressure.

In the absence of boundary instabilities which could couple solar wind momentum to the magnetospheric plasma we would expect the only solar wind effect that was observable in the magnetospheric interior to be the compression of the geomagnetic field by the external pressure. In Chapter 3 we examined the ground magnetic field perturbations that arose from a time-varying solar wind dynamic pressure being exerted upon the magnetosphere. We found that transient perturbations were observed which were considerably greater than that expected due to a simple compression of the geomagnetic field, yet these were undeniably associated with the observed magnetospheric compression. The large amplitude of the oscillations could only be due to the presence overhead of ionospheric currents, implying the presence of ionospheric plasma motions. This coupling of a compressional phenomenon to incompressible ionospheric flows was an unexpected result. It presented a new way in which momentum could be transferred from the solar wind to the magnetospheric and ionospheric plasma. Southwood and Kivelson (1989) showed that the coupling

arose due to the inhomogeneity of the magnetospheric plasma and the localised nature of the magnetopause deformation arising from a pressure variation.

Previous ionospheric observations had revealed transient signatures which had been interpreted as evidence for momentum transfer from the solar wind on short time scales by reconnection at the dayside magnetopause. These signatures had been sought for as the low-altitude counterpart to the short-period flux transfer event (FTE) signatures seen by spacecraft at the dayside magnetopause. However, in our study we noted that at an individual observing station the ground magnetic perturbation due to solar wind dynamic pressure variations could resemble the postulated signature of a FTE, and thus such ground signatures could not be exclusively attributed to a reconnection process. Since the FTE was thought to be a significant contributor to the total magnetospheric convection potential, it was important to be able to distinguish its ground signature from transients arising from other effects. This has led to the need of a better model for the FTE so that its ground signature may be more precisely defined. The clearest indicator of whether an observed ground FTE candidate is due to a solar wind pressure variation or to time-varying reconnection is the relationship of the event's phase motion to the plasma motion inside the FTE footprint. In the reconnection scenario the plasma must move with the event, whereas in the case of a pressure pulse event the plasma motion is often orthogonal to the event phase motion.

Questions that require further attention include how the magnetopause is deformed by a solar wind pressure variation, to what extent the ionosphere plays a role in the event's behaviour, and the contribution made to the total convection strength by the buffeting of the magnetosphere by the solar wind.

6.3. The Response of the Magnetosphere-Ionosphere System to Inferred Changes in the Reconnection Rate.

In Chapter 1 we reviewed some of the work which had brought us to the level of understanding existing prior to my entry into the field of Space Physics research. At this time much progress had been made on establishing the time-averaged state of the magnetosphere under different solar wind conditions e.g. the typical convection pattern for different IMF component polarities. However, it was apparent that the magnetospheric conditions prevailing at any given instant could deviate greatly from the typical, such that there was not a simple correspondence between the instantaneous solar wind condition and its magnetospheric effect. This was perhaps particularly apparent in substorm research. Though phenomenological models of a substorm could be established based on accumulated observations, it has been impossible to quantitatively predict its behaviour. Though there may be a consensus that a substorm onset involving a violent burst of reconnection in the

near-Earth tail follows a growth of the magnetic flux in the tail caused by a southward turning of the IMF that stimulated reconnection at the dayside magnetopause, we cannot say for any given event how long it will be between the southward IMF turning and the onset, or how much flux will be added to the magnetotail. The variance in the growth phase duration or in the amount of magnetospheric erosion indicates that the history of the solar wind conditions is as important as its instantaneous value in determining its magnetospheric effect.

We considered this in Chapter 2 by first considering how the temporal evolution of the magnetosphere is coupled to the ionosphere. The incompressibility of the ionospheric plasma means that the ionosphere adapts essentially instantaneously to the boundary condition imposed by the magnetosphere, though this boundary condition may be subsequently modified by feedback from the ionosphere. Thus prediction of the ionospheric convection reduces to a prediction of the magnetospheric behaviour.

However, the response of the magnetosphere to changes in its external boundary conditions need not be so direct or immediate. In Chapter 4 we observed afternoon auroral zone flows to pick up within ~ 10 min of the impingement of a southward IMF turning upon the subsolar magnetopause. More extensive analyses of the response of dayside ionospheric flows to a change in the north-south, B_z , component of the IMF and by inference to the dayside reconnection rate showed that the flows close to noon MLT responded within about an Alfvén wave travel time to a change in the inferred reconnection rate, but that the initial response was progressively later (up to ~ 15 min) at dayside MLTs further from noon. In addition, the flows typically continued to evolve over ~ 15 min time scale after their initial response. A similar ionospheric response has been observed following sudden changes in the east-west, B_y , component of the IMF. These results implied that the magnetospheric system took a short, but finite time to evolve from one quasi-steady state to another and also suggested that this system inertia is associated with only newly opened magnetic flux tubes.

The dayside reconnection rate probably varies over the whole range of time scales on which the IMF B_z component is observed to vary i.e. a continuum. Thus, for sufficiently slow variations, the dayside ionospheric flows might be expected to reflect the prevailing IMF condition. However, if the IMF varied on a time scale short compared to the response time quoted above (2-15 min) then the ionospheric response is likely to be complex and not directly related to the instantaneous state of the IMF.

An additional complication to the magnetosphere-ionosphere response to the solar wind arises from the fact that nightside reconnection is observed to be less directly or promptly controlled by the IMF orientation. Typically, the nightside reconnection rate increases in

an explosive manner some tens of minutes after a southward turning of the IMF. The effect of an enhanced nightside reconnection rate is probably established on a similar time scale to that on the dayside, though this has yet to be demonstrated. In the event discussed in Chapters 4 and 5 a nightside-induced flow enhancement was observed to propagate to the dayside with an ionospheric phase motion of $4\text{--}8\text{ km s}^{-1}$, similar to that observed on the dayside. These results mean that the dayside and nightside reconnection rates are rarely, if ever, matched. Hence the magnetosphere is rarely in steady state, even if the IMF condition is steady. An imbalance in the dayside and nightside reconnection rates causes a progressive change in magnetospheric topology which perturbs the steady state flow pattern.

From these considerations we developed in Chapter 2 a simple model that would allow us to derive quantitative flow patterns appropriate to different time-varying magnetospheric boundary conditions. By comparing model results we could identify the convection signatures of different boundary conditions. These signatures could then be used to diagnose the conditions prevailing during actual ionospheric observations.

In Chapter 4 we studied an event in which the magnetopause was found to be earthward of its expected position, and was inferred to migrate further earthward with time. The correlation of the apparent erosion of the dayside magnetopause with a growth in the ionospheric polar cap led us to conclude that the topology of the magnetosphere was changing: open magnetic flux was accumulating in the magnetotail.

The concurrent observation at the dayside magnetopause of plasma and magnetic signatures of ongoing reconnection indicated that the increase in open magnetic flux was due to a dayside reconnection rate in excess of that on the nightside. Comparison of the observed ionospheric flows with the model results of Chapter 2 confirmed the presence of a strong ionospheric circulation that was due to dominant quasi-steady dayside reconnection. Interestingly, a substorm onset failed initially to arrest this erosion. Thus the state of the magnetosphere at any given time could be seen to depend not only on the prevailing solar wind condition, but also on the duration and rate of reconnection at the dayside magnetopause with respect to that on the nightside i.e. the solar wind history.

Further attention should be directed to the temporal and spatial variations of the polar cap, as these appear to be remote sensors of the dayside and nightside reconnection regions. In order to do this it is important to decide how the polar cap boundary can be accurately identified; we proposed in Chapter 4 a number of magnetic, plasma, and convection signatures that could be used to varying degrees of accuracy.

It is as yet unclear why the polar cap appears to distort more readily on the nightside than on the dayside. This may be due to the very different ionospheric conductivities in these two regions, or to a difference in the peak reconnection rates, or to the different magnetosphere-ionosphere wave travel times. Observations of these distortions and their evolution should shed more light upon how the magnetosphere and ionosphere couple in time-dependent situations.

The addition of dayside observations to the substorm literature has shown the substorm development to be more complex than was perhaps apparent hitherto. In Chapter 4 we found that the polar cap did not everywhere contract at substorm onset, but indeed appeared to continue to grow on the dayside until the ground magnetic perturbation associated with the tail reconnection reached its peak, and coincidentally the inferred dayside reconnection-rate declined due to a northward IMF turning. Thus the substorm phases determined by nightside observations do not necessarily order the dayside behaviour.

The observations presented in Chapter 4 also offer information on the question of what triggers the substorm onset. The sudden onset of the large nightside magnetic bay appeared to have no immediate trigger in the solar wind or magnetosheath, other than the southward IMF turning itself. This suggests that either the nightside response is directly driven by the IMF with a system lag (~ 40 min) as contended by Akasofu (1980), or that the substorm trigger is to do with the change in the magnetosphere, brought about by the prevailing southward IMF, as argued by McPherron et al. (1973). Possible substorm triggers include simply the sensing in the tail of the dayside reconnection onset, some critical flux content being reached in the magnetotail, or some ionospheric effect. On basis of the event studied, we would favour the McPherron et al. model, as the nightside response to the northward IMF turning appears to be shorter (< 15 min) than to the southward turning.

6.4. The Magnetosphere-Ionosphere Coupling Agent: Field-Aligned Current.

The coupling of magnetospheric motion to the resistive ionosphere requires the supply of energy to overcome the drag force of the ionospheric neutral gases, as discussed in Chapter 1. The high-altitude moving plasma provides the energy by a field-aligned current system which closes in the ionosphere. In Chapter 5 we developed an analytical technique which could examine the structure and strength of such currents using a ground-based radar. The method was used to identify a field-aligned current sheet which was created in the late afternoon mid-latitude ionosphere during the erosion event studied in Chapter 4.

Surveys of the ionospheric flow vorticity might be usefully compared with the field-aligned current surveys conducted using polar orbiting satellite data, particularly on the dayside where strong ionospheric conductivity gradients are less likely to be prevalent.

The ionospheric observations should prove complementary to the satellite results because they offer the ability to determine the variation of the currents on short temporal and spatial scales. Since these currents are fed directly from the magnetosphere, it is hoped that this technique may yield information on the way in which the magnetospheric boundary condition discussed above is imposed upon the ionosphere.

References.

- Abel, W. J., and R. E. Newell, Measurements of afternoon radio aurora at 1295 MHz, *J. Geophys. Res.*, 74, 231, 1969.
- Akasofu, S.-I., The development of the auroral substorm, *Planet. Space Sci.*, 12, 273, 1964.
- Akasofu, S.-I., and C.-I. Meng, A study of polar magnetic substorms, *J. Geophys. Res.*, 74, 293, 1969.
- Akasofu, S.-I., and S. Chapman, *Solar-Terrestrial Physics*, Oxford University Press, 1972.
- Akasofu, S.-I., *Physics of magnetospheric substorms*, D. Reidel, 1977.
- Akasofu, S.-I., The solar wind-magnetosphere energy coupling and magnetospheric disturbances, *Planet. Space Sci.*, 28, 495, 1980.
- Alfvén, H., Magnetohydrodynamic waves, in *Cosmical Electrodynamics*, Oxford University Press, London, U.K., p. 76, 1950.
- Armstrong, J. C., and A. J. Zmuda, Field-aligned current at 1100 km in the auroral region measured by satellite, *J. Geophys. Res.*, 75, 7122, 1970.
- Armstrong, J. C., and A. J. Zmuda, Triaxial magnetic measurements of field-aligned currents at 800 kilometers in the auroral region: initial results, *J. Geophys. Res.*, 78, 6802, 1973.
- Aubry, M. P., C. T. Russell, and M. G. Kivelson, Inward motion of the magnetopause before a substorm, *J. Geophys. Res.*, 75, 7018, 1970.
- Axford, W. I., and C. O. Hines, A unifying theory of high-latitude geophysical phenomena and geomagnetic storms, *Can. J. Phys.*, 39, 1433, 1961.
- Bargatze, L. F., D. N. Baker, R. L. McPherron, and E. W. Hones, Jr., Magnetosphere impulse response for many levels of geomagnetic activity, *J. Geophys. Res.*, 90, 6387, 1985.
- Berchem, J., and C. T. Russell, Flux transfer events on the magnetopause: spatial distribution and controlling factors, *J. Geophys. Res.*, 89, 6689, 1984.
- Biermann, L., Kometenschweife und solare Korpuskularstrahlung, *Zs. f. Astrophys.*, 29, 274, 1951.

Biernat, H. K., M. F. Heyn, R. P. Rijnbeek, V. S. Semenov, and C. J. Farrugia, The structure of reconnection layers: Application to the Earth's magnetopause, *J. Geophys. Res.*, 94, 287, 1989.

Boteler, D. H., The effect of induced currents in the sea on magnetic bays observed at a coastal observatory, *J. Atmos. Terr. Phys.*, 40, 577, 1978.

Bowles, K. L., B. B. Balsley, and R. Cohen, Field-aligned E-region irregularities identified with acoustic plasma waves, *J. Geophys. Res.*, 68, 2485, 1963.

Bunemann, O., Excitation of field-aligned sound waves by electron streams, *Phys. Rev. Lett.*, 10, 285, 1963.

Chapman, S., and V. C. A. Ferraro, A new theory of magnetic storms, *Nature*, 126, 129, 1930.

Chubb, T. A., and G. T. Hicks, Observations of the aurora in the far ultraviolet from OGO 4, *J. Geophys. Res.*, 75, 1290, 1970.

Cohen, R., and K. L. Bowles, The association of plane-wave electron-density irregularities with the equatorial electrojet, *J. Geophys. Res.*, 68, 2503, 1963.

Coriniti, F. V., and C. F. Kennel, Changes in magnetospheric configuration during the substorm growth phase, *J. Geophys. Res.*, 77, 3361, 1972.

Coriniti, F. V., and C. F. Kennel, Can the ionosphere regulate magnetospheric convection ?, *J. Geophys. Res.*, 78, 2837, 1973.

Cowley, S. W. H., Magnetospheric asymmetries associated with the Y component of the IMF, *Planet. Space Sci.*, 28, 79, 1981.

Cowley, S. W. H., The causes of convection in the Earth's magnetosphere: a review of developments during the IMS, *Rev. Geophys. Space Phys.*, 20, 531, 1982.

Cummings, W. D., J. N. Barfield, and P. J. Coleman, Jr., Magnetospheric substorms observed at the synchronous orbit, *J. Geophys. Res.*, 73, 6687, 1968.

Doyle, M. A., and W. J. Burke, S3-2 measurements of the polar cap potential, *J. Geophys. Res.*, 88, 9125, 1983.

Dudeney, J. R., A. S. Rodger, and M. J. Jarvis, Radio studies of the main F region trough in Antarctica, *Radio Science*, 18, 927, 1983.

Dungey, J. W., Interplanetary magnetic field and the auroral zones, *Phys. Rev. Lett.*, 6, 47, 1961.

Dungey, J. W., in *Geophysics, The Earth's Environment*, edited by C. DeWitt, J. Hieblot, A. Lebeau, Gordon and Breach, New York, U.S.A., 1963.

Eather, R. H., *Majestic Lights: The aurora in Science, History and the Arts*, American Geophysical Union, 1980.

Ecklund, W. L., B. B. Balsley, and R. A. Greenwald, Crossed beam measurements of the diffuse radar aurora, *J. Geophys. Res.*, 80, 1805, 1975.

Ecklund, W. L., B. B. Balsley, and D. A. Carter, A preliminary comparison of F-region plasma drifts and E-region irregularity drifts in the auroral zone, *J. Geophys. Res.*, 82, 195, 1977.

Eddy, J. A., The Maunder minimum, *Science*, 192, 1189, 1976.

Etemadi, A., S. W. H. Cowley, M. Lockwood, B. J. I. Bromage, D. M. Willis, and H. Lühr, The dependence of high-latitude dayside ionospheric flows on the north-south component of the IMF: a high time resolution correlation analysis using EISCAT "Polar" and AMPTE UKS and IRM data, *Planet. Space Sci.*, 36, 471, 1988.

Fairfield, D. H., and N. F. Ness, Configuration of the geomagnetic tail during substorms, *J. Geophys. Res.*, 75, 7032, 1970.

Fairfield, D.H., Average and unusual locations of the Earth's magnetopause and bow shock, *J. Geophys. Res.*, 76, 6700, 1971.

Fälthammar, C.-G., The solar wind, in *Cosmical Geophysics*, edited by A. Egeland, Ø. Holter, and A. Omholt, Universitetsforlaget, Oslo, Norway, p. 93, 1973.

Farley, D. T., A plasma instability resulting in field-aligned irregularities in the ionosphere, *J. Geophys. Res.*, 68, 6083, 1963.

Farley, D. T., H. M. Ierke, and B. G. Fejer, The absolute scattering cross section at 50 MHz of equatorial electrojet irregularities, *J. Geophys. Res.*, 86, 1569, 1981.

- Farrugia, C. J., M. P. Freeman, S. W. H. Cowley, D. J. Southwood, M. Lockwood, and A. Etemadi, Pressure-driven magnetopause motions and attendant response on the ground, *Planet. Space Sci.*, 37, 589, 1989.
- Fejer, B. G., and M. C. Kelley, Ionospheric Irregularities, *Rev. Geophys.*, 18, 401, 1980.
- Formisano, V., V. Domingo, and K.-P. Wenzel, The three-dimensional shape of the magnetopause, *Planet. Space Sci.*, 27, 1137, 1979.
- Frank, L. A., Direct detection of asymmetric increases of extraterrestrial 'ring current' proton intensities in the outer radiation zone, *J. Geophys. Res.*, 75, 1263, 1970.
- Freeman, M.P. and D. J. Southwood, The effect of magnetospheric erosion on mid- and high-latitude ionospheric flows, *Planet. Space Sci.*, 36, 509, 1988a.
- Freeman, M. P., and D. J. Southwood, The correlation of variations in the IMF with magnetosheath field variations, *Adv. Space Res.*, 8, 217, 1988b.
- Freeman, M. P., C. J. Farrugia, D. J. Southwood, S. W. H. Cowley, M. Lockwood, and A. Etemadi, The response of the magnetosphere-ionosphere system to solar wind dynamic pressure variations, *Proceedings of the Chapman Conference on Magnetic Flux Ropes*, in press, 1989.
- Friis-Christensen, E., M. A. McHenry, C. R. Clauer, and S. Vennerstrom, Ionospheric travelling convection vortices observed near the polar cleft: a triggered response to sudden changes in the solar wind, *Geophys. Res. Lett.*, 15, 253, 1988.
- Fukushima, N., Equivalence in ground geomagnetic effect of Chapman-Vestine's and Birkeland-Alfvén's electric current systems for polar magnetic storms, *Rep. Ionos. Space Res. Jpn.*, 23, 1969.
- Gillis, E. J., R. P. Rijnbeek, R. Kling, T. W. Speiser, and T. A. Fritz, Do flux transfer events cause long-period micropulsations in the dayside magnetosphere?, *J. Geophys. Res.*, 92, 5820, 1987.
- Greenwald, R. A., Diffuse radar aurora and the gradient drift instability, *J. Geophys. Res.*, 79, 4807, 1974.
- Greenwald, R. A., and W. L. Ecklund, A new look at radar auroral motions, *J. Geophys. Res.*, 80, 3642, 1975.

Greenwald, R. A., W. L. Ecklund, and B. B. Balsley, Radar observations of auroral electrojet currents, *J. Geophys. Res.*, 80, 3635, 1975.

Greenwald, R. A., W. Weiss, E. Nielsen, and N. R. Thomson, STARE: A new radar auroral backscatter experiment in northern Scandinavia, *Radio Sci.*, 13, 1021, 1978.

Gustafsson, G., Corrected geomagnetic coordinates for epoch 1980, in *Magnetospheric currents*, ed. T. Potemra, American Geophysical Union, p. 276, 1984.

Haldoupis, C. I., and E. Nielsen, Results on relative scattering cross section of 140 MHz auroral backscatter, *J. Geophys. Res.*, 89, 2305, 1984.

Hardy, D. A., L. K. Schmitt, M. S. Gussenhoven, F. J. Marshall, H. C. Yeh, T. L. Shumaker, A. Hube, and J. Pantazis, Precipitating electron and ion detectors (SSJ/4) for the block 5D/flights 6-10 DMSP satellites: Calibration and data presentation, Rep. AFGL-TR-84-0317, Air Force Geophysics Laboratory, Hanscom Air Force Base, Mass., 1984.

Harel, M., R. A. Wolf, P. H. Reiff, R. W. Spiro, W. J. Burke, F. J. Rich, and M. Smiddy, Quantitative simulation of a magnetospheric substorm, 1, Model logic and overview, *J. Geophys. Res.*, 86, 2217, 1981.

Heelis, R. A., and W. B. Hanson, Ion convection velocity reversals in the dayside cleft, *J. Geophys. Res.*, 81, 3803, 1976.

Heelis, R. A., The effects of interplanetary magnetic field orientation on dayside high-latitude ionospheric convection, *J. Geophys. Res.*, 89, 2873, 1984.

Heppner, J. P., and N. C. Maynard, Empirical high latitude electric field models, *J. Geophys. Res.*, 92, 4467, 1987.

Holzworth, R. H., and C.-I. Meng, Mathematical representation of the auroral oval, *Geophys. Res. Lett.*, 2, 377, 1975.

Hones, E. W. Jr., J. R. Asbridge, S. J. Bame, and I. B. Strong, Outward flow of plasma in the magnetotail following geomagnetic bays, *J. Geophys. Res.*, 72, 5879, 1967.

Hones, E. W. Jr., Substorm processes in the magnetotail: comments on 'On hot tenuous plasmas, fireballs, and boundary layers in the Earth's magnetotail' by L. A. Frank, K. L. Ackerson, and R. P. Lepping, *J. Geophys. Res.*, 82, 5633, 1977.

Igarashi, K., T. Ogawa, M. Ose, R. Fujii, and T. Hirasawa, A new VHF Doppler radar experiment at Syowa station, Antarctica, *Memoirs of National Institute of Polar Research*, Special Issue No. 22, 258, 1982.

Iijima, T., and T. A. Potemra, Large-scale characteristics of field-aligned currents associated with substorms, *J. Geophys. Res.*, 83, 599, 1978.

Jaggi, R.K., and R.A. Wolf, Self-consistent calculation of the motion of a sheet of ions in the magnetosphere, *J. Geophys. Res.*, 78, 2852, 1973.

Kamide, Y., A.D. Richmond, and S. Matsushita, Estimation of ionospheric electric fields, ionospheric currents and field-aligned currents from ground magnetic records, *J. Geophys. Res.*, 86, 801, 1981.

Kisabeth, J. L., and G. Rostoker, Development of the polar electrojet during polar magnetic substorms, *J. Geophys. Res.*, 76, 6815, 1971.

Lanzerotti, L.J., L. C. Lee, C. G. MacLennan, A. Wolfe, and L. V. Medford, Possible evidence of flux transfer events in the polar ionosphere, *Geophys. Res. Lett.*, 13, 1089, 1986.

Lanzerotti, L.J., R. D. Hunsucker, D. Rice, L. -C. Lee, A. Wolfe, C. G. MacLennan, and L. V. Medford, Ionosphere and ground-based response to field-aligned currents near the magnetospheric cusp regions, *J. Geophys. Res.*, 92, 7739, 1987.

Lee, L.-C., Magnetic flux transfer at the Earth's magnetopause, in *Proc. Chapman Conf. on Solar Wind-Magnetosphere Coupling*, ed. Y. Kamide and J. Slavin, 1986.

Lester, M., W. J. Hughes, and H. J. Singer, Longitudinal structure in Pi 2 pulsations and the substorm current wedge, *J. Geophys. Res.*, 89, 5489, 1984.

Lockwood, M., and M. P. Freeman, Recent ionospheric observations relating to solar wind-magnetosphere coupling, *Phil. Trans. R. Soc. Lond.*, A 328, 93, 1989.

Lockwood, M., and M. F. Smith, Low-altitude signatures of the cusp and flux transfer events, *Geophys. Res. Lett.*, 16, 879, 1989.

Lockwood, M., S. W. H. Cowley, and M. P. Freeman, The excitation of plasma convection in the high-latitude ionosphere, *J. Geophys. Res.*, in press, 1989a.

Lockwood, M., P. E. Sandholt, and S. W. H. Cowley, Dayside auroral activity and magnetic flux transfer from the solar wind, *Geophys. Res. Lett.*, 16, 33, 1989b.

- Lui, A. T. Y., R. W. McEntire, and S. M. Krimigis, Evolution of the ring current during two geomagnetic storms, *J. Geophys. Res.*, 92, 7459, 1987.
- McHenry, M.A. and C. R. Clauer, Modelled ground magnetic signatures of flux transfer events, *J. Geophys. Res.*, 92, 11 231, 1987.
- McHenry, M. A., C. R. Clauer, E. Friis-Christensen, and J. D. Kelly, Observations of ionospheric convection vortices: signatures of momentum transfer, *Adv. Space Res.*, in press, 1988.
- McPherron, R. L., C. T. Russell, and M. P. Aubry, Satellite studies of magnetospheric substorms on August 15, 1968, *J. Geophys. Res.*, 78, 3131, 1973.
- Mead, G. D., and D. B. Beard, Shape of the geomagnetic field solar wind boundary, *J. Geophys. Res.*, 69, 1169, 1964.
- Meng, C.-I., R. H. Holzworth, and S.-I. Akasofu, Auroral circle - delineating the poleward boundary of the quiet auroral belt, *J. Geophys. Res.*, 82, 164, 1977.
- Meng, C.-I., Case studies of the storm time variation of the polar cusp, *J. Geophys. Res.*, 88, 137, 1983.
- Newell, P. T., and C.-I. Meng, Cusp width and Bz: observations and a conceptual model, *J. Geophys. Res.*, 92, 13 673, 1987.
- Newell, P. T., C.-I. Meng, D. G. Sibeck, and R. Lepping, Some low altitude cusp dependencies on interplanetary magnetic field, submitted to *J. Geophys. Res.*, 1989.
- Nielsen, E., and K. Schlegel, A first comparison of STARE and EISCAT electron drift velocity measurements, *J. Geophys. Res.*, 88, 5745, 1983.
- Nielsen, E., W. Guttler, E.C. Thomas, C.P. Stewart, T.B. Jones, and A. Hedberg, *Nature*, 304, 712, 1983.
- Nielsen, E., and K. Schlegel, Coherent radar doppler measurements and their relationship to the ionospheric electron drift velocity, *J. Geophys. Res.*, 90, 3498, 1985.
- Nishida, A., and E. F. Lyon, Plasma sheet at lunar distance: structure and solar-wind dependence, *J. Geophys. Res.*, 77, 4086, 1972.
- Parker, E. N., Dynamics of the interplanetary gas and magnetic fields, *Astrophys. J.*, 128, 664, 1958.

- Parker, E. N., The hydromagnetic theory of solar corpuscular radiation and stellar winds, *Astrophys. J.*, 132, 821, 1960.
- Parker, E. N., The penetration of galactic cosmic rays into the solar system, in *The Solar Wind*, edited by R. J. Mackin Jr., and M. Neugebauer, Pergamon Press, Oxford, U.K., p. 185, 1964.
- Parks, G. K., and J. R. Winckler, Acceleration of energetic electrons observed at the synchronous altitude during magnetospheric substorms, *J. Geophys. Res.*, 73, 5786, 1968.
- Paschmann, G., G. Haerendel, I. Papamastorakis, N. Sckopke, S. J. Bame, J. T. Gosling, and C. T. Russell, Plasma and magnetic field characteristics of magnetic flux transfer events, *J. Geophys. Res.*, 87, 2159, 1982.
- Paschmann, G., I. Papamastorakis, W. Baumjohann, N. Sckopke, C. W. Carlson, B. U. Ö. Sonnerup, and H. Lühr, The magnetopause for large magnetic shear: AMPTE/IRM observations, *J. Geophys. Res.*, 91, 11 099, 1986.
- Potemra, T.A., H. Lühr, L. J. Zanetti, K. Takahashi, R. E. Erlandson, G. T. Marklund, L. P. Block, L. G. Blomberg, and R. P. Lepping, Multi-satellite and ground-based observations of transient ULF waves, *J. Geophys. Res.*, 94, 2543, 1989.
- Reiff, P. H., T. W. Hill, and J. L. Burch, Solar wind plasma injection at the dayside magnetospheric cusp, *J. Geophys. Res.*, 82, 479, 1977.
- Reiff, P. H., R. W. Spiro, and T. W. Hill, Dependence of polar cap potential drop on interplanetary parameters, *J. Geophys. Res.*, 86, 7639, 1981.
- Rijnbeek, R.P., S. W. H. Cowley, D. J. Southwood, and C. T. Russell, A survey of dayside flux transfer events observed by ISEE 1 and 2 magnetometers, *J. Geophys. Res.*, 89, 786, 1984.
- Rijnbeek, R.P., C. J. Farrugia, D. J. Southwood, C. P. Chaloner, D. S. Hall, M. F. Smith, M. W., Dunlop, and W. A. C. Mier-Jedrzejowicz, *Planet. Space Sci.*, 35, 871, 1987.
- Robinson, T. R., Towards a self-consistent non-linear theory of radar auroral backscatter, *J. Atmos. Terr. Phys.*, 48, 417, 1986.
- Rodger, A.S., and S.M. Broom, The ionospheric signature of the polar cleft over Halley, Antarctica, *Br. Antarct. Surv. Bull.*, 72, 1, 1986.

Rogister, A., and N. D'Angelo, Type 2 irregularities in the equatorial electrojet, *J. Geophys. Res.*, 75, 3879, 1970.

Russell, C. T., and R. C. Elphic, Initial ISEE magnetometer results: magnetopause observations, *Space Science Rev.*, 22, 681, 1978.

Sandholt, P.E., C.S. Deehr, A. Egeland, B. Lybekk, R. Viereck, and G.J. Romick, Signatures in the dayside aurora of plasma transfer from the magnetosheath, *J. Geophys. Res.*, 91, 10063, 1986.

Saunders, M.A., C. T. Russell, and N. Sckopke, Flux transfer events: scale size and interior structure, *Geophys. Res. Lett.*, 11, 131, 1984.

Scholer, M., Magnetic flux transfer at the magnetopause based on single X line bursty reconnection, *Geophys. Res. Lett.*, 15, 291, 1988.

Schield, M. A., Pressure balance between solar wind and magnetosphere, *J. Geophys. Res.*, 74, 1275, 1969.

Schlegel, K., and J. P. St.-Maurice, Anomalous heating of the polar E region by unstable plasma waves. 1. Observations, *J. Geophys. Res.*, 86, 1447, 1981.

Scholer, M., Magnetic flux transfer at the magnetopause based on single X line bursty reconnection, *Geophys. Res. Lett.*, 15, 291, 1988.

Sergeev, V. A., and A. G. Yahnin, The features of auroral bulge expansion, *Planet. Space Sci.*, 27, 1429, 1979.

Siscoe, G. L., Evidence in the auroral record for secular solar variability, *Rev. Geophys. Space Phys.*, 18, 647, 1980.

Siscoe, G. L., and T. S. Huang, Polar cap inflation and deflation, *J. Geophys. Res.*, 90, 543, 1985.

Smith, E. W., B. T. Tsurutani, and R. L. Rosenberg, Observations of the interplanetary sector structure up to heliographic latitudes of 16° , *J. Geophys. Res.*, 83, 717, 1978.

Snyder, C. W., M. Neugebauer, and U. R. Rao, The solar wind velocity and its correlation with cosmic-ray variations and with solar and geomagnetic activity, *J. Geophys. Res.*, 68, 6361, 1963.

- Sonnerup, B. U. Ö., G. Paschmann, I. Papamastorakis, N. Sckopke, G. Haerendel, S. J. Bame, J. R. Asbridge, J. T. Gosling, and C. T. Russell, Evidence for magnetic field reconnection at the Earth's magnetopause, *J. Geophys. Res.*, 86, 10 049, 1981.
- Southwood, D. J., The hydromagnetic stability of the magnetospheric boundary, *Planet. Space Sci.*, 16, 587, 1968.
- Southwood, D. J., The role of hot plasma in magnetospheric convection, *J. Geophys. Res.*, 82, 5512, 1977.
- Southwood, D.J., Magnetopause Kelvin-Helmholtz instability, in *Magnetospheric Boundary Layers*, p.357, ESA Special Publication, 1979.
- Southwood, D. J., and W. J. Hughes, Theory of hydromagnetic waves in the magnetosphere, *Space Science Rev.*, 35, 301, 1983.
- Southwood, D. J., Theoretical aspects of ionospheric-magnetospheric-solar wind coupling, *Adv. Space Res.*, 5, 7, 1985.
- Southwood, D.J., M.A. Saunders, M.W. Dunlop, W.A.C. Mier-Jedrzejowicz, and R.P. Rijnbeek, A survey of flux transfer events recorded by the UKS spacecraft magnetometer, *Planet. Space Sci.*, 34, 1349, 1986.
- Southwood, D. J., The ionospheric signature of flux transfer events, *J. Geophys. Res.*, 92, 3207, 1987.
- Southwood, D. J., C. J. Farrugia, and M. A. Saunders, What are flux transfer events?, *Planet. Space Sci.*, 36, 503, 1988.
- Southwood, D. J., and M. G. Kivelson, The magnetohydrodynamic response of the magnetospheric cavity to changes in the solar wind pressure, *J. Geophys. Res.*, in press, 1989.
- Spreiter, J. R., and S. S. Stahara, A new predictive model for determining solar wind-terrestrial planet interactions, *J. Geophys. Res.*, 85, 6769, 1980.
- Sudan, R. N., J. Akinrimisi, and D. T. Farley, Generation of small-scale irregularities in the equatorial electrojet, *J. Geophys. Res.*, 78, 240, 1973.
- Todd, H., B. J. I. Bromage, S. W. H. Cowley, M. Lockwood, A. P. van Eyken, and D. M. Willis, Eiscat observations of bursts of rapid flow in the high latitude ionosphere, *Geophys. Res. Lett.*, 13, 909, 1986.

Todd, H., S. W. H. Cowley, A. Etemadi, B. J. I. Bromage, M. Lockwood, D. M. Willis, and H. Lühr, Flow in the high-latitude ionosphere: measurements at 15s resolution made using the EISCAT 'Polar' experiment, *J. Atmos. Terr. Phys.*, 50, 423, 1988.

Vasyliunas, V. M., Concepts of magnetospheric convection, in *The Magnetospheres of the Earth and Jupiter*, edited by V. Formisano, D. Reidel Publishing Co., Dordrecht-Holland, p. 179, 1975.

Waldock, J.A., T.B. Jones, and E. Neilsen, Mean auroral E-region plasma convection patterns measured by SABRE, *Nature*, 313, 204, 1985.

Waldock, J. A., Southwood, D. J., Freeman, M. P., and M. Lester, Pulsations observed during high-speed flow in the ionosphere, *J. Geophys. Res.*, 93, 12883, 1988.

Wallis, D. D., and E. E. Budzinski, Empirical models of height integrated conductivities, *J. Geophys. Res.*, 86, 125, 1981.

Wolf, R.A., M. Harel, R.W. Spiro, G.-H. Voigt, P.H. Reiff, and C.-K. Chen, Computer simulation of inner magnetospheric dynamics for the magnetic storm of July 29, 1977, *J. Geophys. Res.*, 87, 5949, 1982.

Wright, A. N., and D. J. Southwood, Stationary Alfvén structures, *J. Geophys. Res.*, 92, 1167, 1987.

Wygant, J. R., R. B. Torbert, and F. S. Mozer, Comparison of S3-3 polar cap potential drops with the interplanetary magnetic field and models of magnetopause reconnection, *J. Geophys. Res.*, 88, 5727, 1983.