

THEORY AND OBSERVATION OF CHARGED PARTICLE
BEHAVIOUR IN THE GEOMAGNETIC TAIL

by

CHRISTOPHER JOHN OWEN

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

October 1988

Physics Department
Imperial College
London, SW7 2BZ

ABSTRACT

Between October 1982 and October 1983 the spacecraft ISEE-3 made six passes into the distant geomagnetic tail to a maximum distance of 238 Earth radii. This provided a unique data set, leading to the discovery of new geomagnetic phenomena, and the posing of new theoretical problems in space plasma physics. This thesis looks at a number of these phenomena from both theoretical and observational viewpoints.

Simple equilibrium models of steady state magnetic reconnection, using the local one-dimensional balance of field and plasma stresses within a current layer, are generalized to include the effects of time dependence, both in terms of changes in the reconnection rate, and of motion of the neutral line itself. The results are illustrated by showing how the structure of the geotail plasma sheet is expected to behave during a substorm, using typical reconnection rates and neutral line motions deduced from observations. These predictions are then compared with observations made by the ISEE-3 spacecraft during an isolated substorm event. Broad agreement between theory and observation is demonstrated, although the data suggest the need for some additions to the theoretical background of this work.

The ISEE-3 data set also shows that large dawn-dusk asymmetries in plasma density can exist in the tail lobes due to effects controlled by IMF B_y , and it is shown that the current sheet equilibrium condition mentioned above can be readily generalized to include these asymmetries, along with the simultaneous flow shears expected from theory under the simplifying assumption that all particles incident on the current sheet are transmitted through it. The results are illustrated by a simple example in which the inflow plasmas are approximated as cold ion beams of unequal density and speed.

Observations made by the EPAS instrument on ISEE-3 during the geotail mission also show that the pitch angle distribution of energetic ions in the distant tail lobes is strongly peaked perpendicular to the magnetic field, with a small downtail anisotropy resulting in a net tailward flow. Models based on particle entry through an open tail magnetopause are presented to account for these distributions, and their dependence on the external conditions in the magnetosheath and solar wind are investigated.

TO THE TERRESTRIAL GLOBE.

Roll on, thou ball, roll on!
Through pathless realms of space

Roll on!

What though I'm in a sorry case?
What though I cannot meet my bills?
What though I suffer toothache's ills?
What though I swallow countless pills?

Never *you* mind!

Roll on!

(IT ROLLS ON)

It's true I've got no shirts to wear;
It's true my butcher's bill is due;
It's true my prospects all look blue -
But don't let that unsettle you!

Never *you* mind!

Roll on!

Sir William Schwenck Gilbert 1836 - 1911
From "The 'Bab' Ballads"

A Tail Of Two Lobes.

ACKNOWLEDGEMENTS

I am deeply indebted to my Supervisor, Professor S. W. H. Cowley, for suggesting the fields of study for this thesis, and for much subsequent advice and encouragement, which has proved invaluable over the last three years.

I would also like to thank Dr I. G. Richardson for introducing me to the black art of data analysis and for allowing me to tap his reserve of useful analysis programs - I feel sure that these have saved me many hours of frustration in the quagmires of this aspect of our field.

Many thanks are also due to the remaining members of the Space Physics Group, both past and present, not only for the benefit of various informed discussions, but also for their contribution in making the last three years such an enjoyable time.

I would also like to express my gratitude to Miss P. Butterworth for help in the final stages of production of this thesis.

I also acknowledge the financial support provided by the Science and Engineering Research Council.

Finally, I am more than grateful to my parents, who have provided constant support and encouragement over the last 24 years, above and beyond the call of duty. With much love, I dedicate this thesis to them.

CONTENTS

Title Page.....	1
Abstract.....	2
Acknowledgements.....	5
Contents.....	6
List of Figures.....	8

Chapter 1: Introduction

1) Early work - The solar wind and magnetosphere.....	12
2) Magnetospheric convection.....	13
3) The magnetotail - Pre-ISEE-3 studies.....	16
4) Current sheet stress balance.....	17
5) Magnetospheric substorms.....	21
6) The ISEE-3 deep tail mission.....	25
7) Summary.....	28

Chapter 2: Simple models of time-dependent reconnection in a collision-free plasma with an application to substorms in the geomagnetic tail.

1) Introduction.....	32
2) Steady state reconnection.....	33
3) Effects of time-dependent reconnection at a stationary neutral line.....	42
4) Effects of neutral line motion.....	46
5) Phenomenological substorm model.....	54
6) Summary.....	60

Chapter 3: ISEE-3 observations in the deep geomagnetic tail.

1) Introduction.....	63
2) Instrumentation.....	64
3) The substorm event of 28th January 1983 - ISEE-3 particle and field observations.....	68
4) Discussion and summary.....	79

Chapter 4: Current sheet stress balance in the geomagnetic tail for asymmetrical tail lobe plasma conditions.

1) Introduction.....	84
2) The general one-dimensional stress balance condition.....	85
3) Stress balance for asymmetrical cold beam inflow.....	89
4) Summary.....	97

Chapter 5: Energetic ions in the lobes of the distant magnetotail.

1) Introduction.....	99
2) Pitch angle distributions in the deep tail.....	100
3) ISEE-3 observations of energetic ions in the distant tail lobes.....	104
4) The magnetosheath as the source of energetic particles in the deep tail lobes.....	120
5) Motion of particles in a uniform-field lobe with a perfect mirror at one end.....	132
6) Motion of particles in a model lobe with increasing field strength close to the Earth.....	151
7) Summary.....	161

Chapter 6: Summary and suggestions for further work..... 165

References.....173

LIST OF FIGURES

Chapter 1

Fig 1.1 Solar wind - Magnetosphere coupling (after Cowley, 1982).....	15
Fig 1.2 Overview of the magnetosphere.....	20
Fig 1.3 Plasma sheet configuration changes during a substorm (after Hones, 1980).....	23
Fig 1.4 Plasma entry into the magnetotail (after Gosling et al., 1985).....	27

Chapter 2

Fig 2.1(i) Sketch of the fields in a 1-D current sheet, (ii) Plasma flow in the field-line rest frame, (iii) Plasma flow in the Earths' rest frame.....	34
Fig 2.2(i) Field structure and particle populations resulting from steady state reconnection, (ii) Changes to field structure and particle populations due to increases in the reconnection rate, (iii) Changes to field structure and particle populations due to decreases in the reconnection rate.....	41
Fig 2.3 Graphical solution to Equation 2.20.....	49
Fig 2.4(i) Effects of steady neutral line motion on field structure and particle populations, (ii) Effects of onset of neutral line motion on field structure and particle populations, (iii) Effects of cessation of neutral line motion on field structure and particle populations.....	53
Fig 2.5 The phenomenological substorm model.....	57

Chapter 3

Fig 3.1 Schematic diagram illustrating the angular coverage of the EPAS instrument.....	65
Fig 3.2 ISEE-3 field and particle data 0400-1100 UT on 28th January 1983.....	69
Fig 3.3 Auroral electrojet indices for 0400-1100 UT on 28th January 1983 (after Baker et al., 1988).....	71

Chapter 4

Fig 4.1 Field configurations used in this chapter.....	91
Fig 4.2 Plasma sheet and reconnected field configuration for asymmetrical lobe plasma conditions.....	96

Chapter 5

Fig 5.1 Overview of different types of distribution function and methods of representation.....	102
Fig 5.2 Magnetic field data for the period 1000-1500 UT on 23rd January 1983.....	106
Fig 5.3 Direction averaged energetic ion fluxes for the period 1000-1500 UT on 23rd January 1983.....	107
Fig 5.4 EPAS sector plots showing "pancake" distributions.....	108
Fig 5.5 Field configuration for open and closed magnetopause regimes.....	110
Fig 5.6 Field and plasma data for 0000-0300 UT on 31st January 1983.....	112
Fig 5.7 Direction averaged energetic ion fluxes for the period 0000-0300 UT on 31st January 1983.....	113
Fig 5.8 EPAS sector plots during the period 0000-0300 UT on 31st January 1983.....	114
Fig 5.9 Field and plasma data for 0700-0900 UT on 5th February 1983 (solar particle event).....	117
Fig 5.10 Direction averaged energetic ion fluxes for the period 0700-0900 UT on 5th February 1983.....	118
Fig 5.11 EPAS sector plots during the period 0700-0900 UT on 5th February 1983.....	119
Fig 5.12 Spatial extent of enhanced ion fluxes arising from (i) bow shock energization and (ii) from ring current escape.....	123
Fig 5.13 (i) The distribution of energetic ions in the magnetosheath (ii) The lobe source distribution.....	128
Fig 5.14 The transformation of velocities between the solar wind and Earth rest frames.....	130
Fig 5.15 Field configuration for a simple model lobe with a perfect mirror at one end.....	133

Fig 5.16 Particle trajectories within a simple model lobe, for a measuring point close to the magnetopause.....	137
Fig 5.17 Distribution function f vs. pitch angle plots showing the effect of distance of the measuring point from the magnetopause in the model lobe.....	140
Fig 5.18 Particle trajectories within a simple model lobe, for a measuring point far from the magnetopause.....	142
Fig 5.19 Distribution function f vs. pitch angle plots showing the effect of downtail distance of the measuring point.....	146
Fig 5.20 Distribution function f vs. pitch angle plots showing the effect of short scale length for the magnetosheath flux variation.....	148
Fig 5.21 Distribution function f vs. pitch angle plots showing the effect of long scale lengths for the magnetosheath flux variation (cf. solar particle events).....	149
Fig 5.22 Field strength vs. distance downtail for the revised model lobes.....	152
Fig 5.23 Particle trajectories in the revised model lobes.....	154
Fig 5.24 The contribution of different types of trajectory to the pitch angle distribution.....	157
Fig 5.25 Distribution function f vs. pitch angle plots for the simple and revised model lobes, illustrating the differences between the resulting pitch angle distributions.....	162

CHAPTER 1
INTRODUCTION

1. Early Work - The Solar Wind and Magnetosphere.

The causes of geomagnetic storms, during which the magnetic field strength at the surface of the Earth was observed to undergo sudden variations on a global scale, had remained unexplained until pioneering work by Chapman and Ferraro (1931, 1932, 1933). These authors put forward the idea that a stream of ionized particles emitted from the sun would be excluded from the region of space dominated by the Earth's magnetic field. In their model the deflection of the particles around the obstacle in the flow compresses the dipole field on the sunward side, and sets up currents in the boundary region between the particles and the Earth's magnetic field. Ferraro (1952, 1960) argued that the boundary of the cavity thus formed is defined by the point at which the incident dynamic particle pressure is balanced by the magnetic pressure of the compressed dipole field. Chapman and Ferraro had originally considered isolated streams of particles emanating from disturbed regions of the sun. However, Biermann (1951, 1957) interpreted observations of comet tails as evidence for a continuous outflow of solar particles. This was later described theoretically by Parker (1958a), who also introduced the term "solar wind" (Parker 1958b). Parker's work predicted that the solar wind would drag the solar magnetic field away from the sun into a huge spiral structure (due to the rotation of the sun) stretching beyond the outer limits of the solar system, defining the region now called the heliosphere. Early observations (e.g. Gringauz et al., 1962, Snyder et al., 1963) made by spacecraft outside the near-Earth cavity, or magnetosphere, confirmed the existence of the solar wind, which was observed to flow radially away from the sun at speeds of order 500 km s^{-1} , whilst Coleman et al. (1960) further showed that there is an interplanetary magnetic field (IMF) embedded in the solar wind flow, as predicted by Parker (1958a).

Axford (1962) and Gold (1962) suggested that the oncoming solar wind flow would be slowed by a shock wave standing in the flow upstream from the Earth, which allows the flow to be diverted around the magnetic cavity. This is necessary (Spreiter et al., 1966) since despite considerable variations in the velocity, density and temperature of the solar wind and the strength of the IMF, the solar wind flow speed is almost always both supersonic and super-alfvenic (the Alfvén speed being the characteristic speed for a magnetized plasma).

The near-Earth cavity, the magnetosphere, contains high energy, low density (relative to the solar wind) particles which are trapped on the Earth's dipolar

magnetic field (Van Allen and Frank, 1959a, b). The first observations of the outermost boundary of this region, the magnetopause, were reported by Sonett et al. (1960). These and further observations (see e.g. review by Hines, 1960) showed that the magnetopause is an abrupt discontinuity across which the direction and strength of the magnetic field, and the plasma particle densities change sharply. On the Earthward side is a strong unidirectional magnetic field, and a tenuous, high energy plasma, whilst the region outside the boundary is usually occupied by a weaker field, which is more variable in both strength and direction, and the denser, lower energy plasma of the shocked solar wind. The subsolar magnetopause typically lies some 10 Earth radii (R_E) upstream from the Earth, although further away ($\approx 15 R_E$) on the dawn-dusk meridians, in general agreement with the model of Ferraro (1960). On the nightside of the Earth the magnetosphere is drawn out into a large tail structure, such that the geomagnetic field points almost directly towards or away from the Earth. This region is, of course, the main subject of this thesis, and the remainder of this introduction is devoted to the formation, discovery, and structure of the geomagnetic tail.

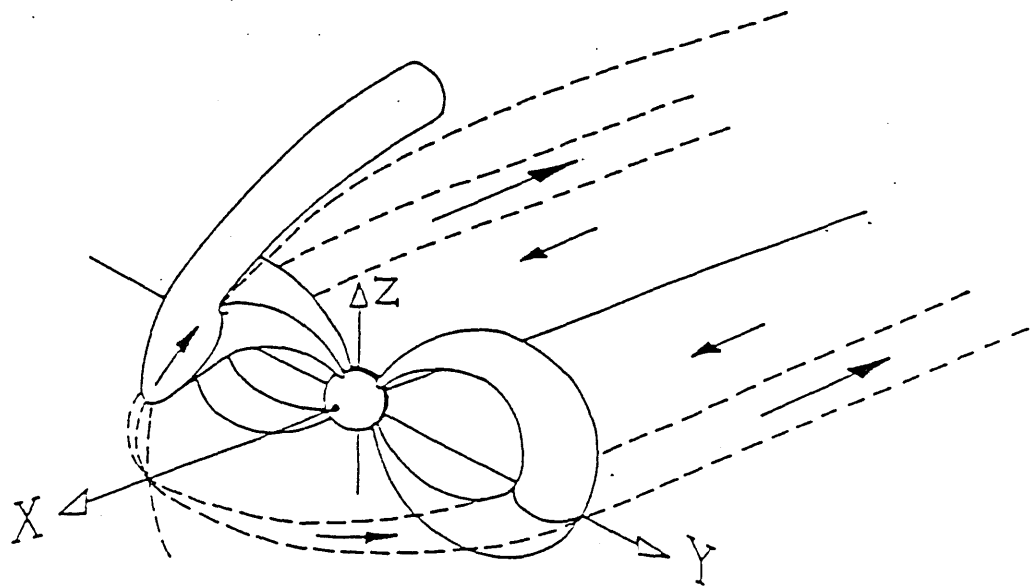
2. Magnetospheric Convection.

Thirty years after the work of Chapman and Ferraro on the formation of the magnetosphere, two differing ideas were proposed for the mechanism of transfer of solar wind momentum and energy into the magnetosphere, to provide the driving force for magnetospheric convection. Axford and Hines (1961) concluded on the basis of ground observations that the magnetospheric plasma must be continually circulating, implying that a large scale magnetospheric electric field exists in the Earth's frame of reference. These authors postulated that the solar wind drives the magnetospheric convection by some form of "viscous" interaction operating at the magnetopause, dragging closed flux tubes (i.e. those which are connected to the Earth at both ends) antisunward along the flanks of the magnetosphere, to form an extended, tail-like field structure on the nightside of the Earth. The return flow of flux to the dayside occurs in the central regions of the magnetosphere, as the field lines contract under the influence of the field tension imparted to them during their antisunward propulsion. The exact nature of this process was not discussed by Axford and Hines, who used the name "viscous" by analogy to hydrodynamics, and has been the subject of ongoing debate (e.g. Lemaire,

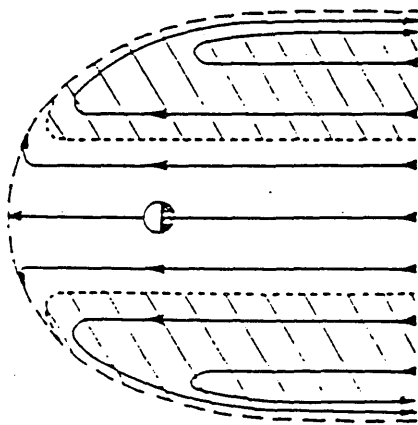
1977; Schindler, 1979; Southwood, 1979; Heikkila, 1982; Cowley, 1984a; Rostoker and Eastman, 1987).

The second process for driving magnetospheric convection was put forward by Dungey (1961), who argued that the presence of a magnetic field in the solar wind and in the magnetosphere would exert control over the plasma transport processes. In particular, a southward component in the IMF results in the presence of a magnetic neutral line at the subsolar magnetopause, where the terrestrial and solar wind fields are antiparallel. Under such conditions the two types of field line may break and become connected to one another by the process of magnetic reconnection (Dungey, 1953), thus creating open flux tubes with one end connected to the Earth and the other into the solar wind. The field tension in these newly created hairpin-like flux tubes, together with the continual antisunward flow of the solar wind and IMF, results in the transportation of the flux tube over the poles and into a magnetospheric tail. These open tubes eventually reconnect again in the tail, and the resulting closed flux tube then flows back towards the Earth.

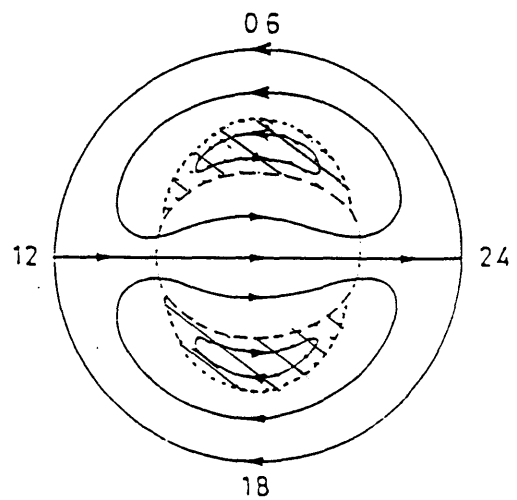
It should be noted that these two types of process are not mutually exclusive, and may coexist on a continual basis. This is illustrated in Figure 1.1 (after Cowley 1982), showing flux tubes in the vicinity of the dayside boundary. The flux tube lying in the noon-midnight meridian in the top diagram has become open into the solar wind by magnetic reconnection, and is in the process of being transported over the pole by the solar wind flow. Note that this flux tube has a counterpart in the southern hemisphere, which is not shown for reasons of clarity. Near the dawn-dusk meridian this diagram also illustrates the closed flux tubes being transported around the flanks of the magnetosphere under the influence of the "viscous" interaction. The lower sketches, (b) and (c), show the flow in the magnetospheric equatorial plane and over the polar regions of the Earth respectively. The hatched regions in each diagram correspond to the parts of the flow which are driven by the "viscous" process, in which the flux tubes remain closed throughout the whole of the cycle, while the remainder of the flow is driven by reconnection, in which the flux tubes are open over the polar cap (the region within the dashed circle in Figure 1.1(c)), and closed at lower latitudes. Observational evidence for both types of process has been presented. For example, Eastman et al. (1976) and Eastman and Hones (1979) interpret observations of boundary layers, containing an admixture of magnetospheric and shocked solar wind (or magnetosheath) particles, adjacent



(a)



(b)



(c)

Figure 1.1 (a) Illustration of the two basic processes, resulting from the solar wind - magnetosphere coupling at the dayside magnetopause boundary, which cause large scale magnetospheric convection. An open magnetic flux tube is shown being transferred to the tail in the noon-midnight meridian, following dayside reconnection. The corresponding flux tube in the southern hemisphere is not shown for reasons of clarity. At the flanks of the magnetosphere, adjacent to the magnetopause, closed flux tubes are being transferred around the sides in boundary layers. These two processes may be generally expected to coexist, as indicated in Figures 1.1(b) and (c). (b) Plasma flow in the Equatorial plane. (c) High latitude flow in the Northern ionosphere. In these lower figures the hatched regions indicate convection driven by the boundary layers in which magnetic tubes remain closed throughout the cycle, whilst the remainder of the flow is associated with the reconnection process. (After Cowley, 1982)

to the magnetopause as evidence for the "viscous" interaction. Meanwhile, Paulikas (1974, and references therein) demonstrated the open nature of the polar cap field lines using solar energetic particles as tracers. Also, a large number of observations (e.g. Fairfield and Cahill (1966); Wilcox et al., (1967); Arnoldy (1971); Jorgensen et al., 1972) indicate a strong response of the convection pattern to the direction of the IMF, as would be expected for the reconnection process.

Accepting that both the Dungey (1961) and the Axford and Hines (1961) processes may occur simultaneously within the magnetosphere, the question remains as to their relative importance for convection. This may be measured, for example, by the contribution that each makes to the cross magnetospheric voltage. This question was reviewed by Cowley (1984), who concluded that the voltages generated by "viscous" processes amounted to some 5-10 kV, whilst those due to reconnection contributed 50-100 kV, and also showed a modulation by the IMF. Hence magnetic reconnection is usually the most important process generating magnetospheric flows, with the other, "viscous" processes playing a lesser role. However, these latter processes may become important during extended periods of magnetic quiet, when reconnection is subdued by the presence of a northward component of the interplanetary magnetic field.

3. The Magnetotail - Pre-ISEE-3 Studies.

The advection of the open field lines (which have recently undergone magnetic reconnection in the vicinity of the subsolar magnetopause) with the solar wind flow over the polar caps results in the formation of an extended magnetic structure in the region of space on the nightside of the Earth. Dungey (1965) estimated the length of this magnetotail to be about 1000 R_E on the basis of the travel time of the foot of the flux tubes across the polar caps, although Dessler (1964) had previously estimated lengths greater than 1 Astronomical Unit. This latter estimate is now considered excessive, although it is perhaps possible that a non-connected tail-like wake may exist much further beyond the extent of the tail proper. Early observational evidence for the existence of the geomagnetic tail was obtained from near-Earth satellites orbiting within 25 R_E (e.g. Smith, 1962; Heppner et al., 1963; Smith et al., 1964). These studies revealed that the field lines on the nightside of the Earth are deflected away from the dipole orientation to point more directly towards or away from the Earth. Frank

(1965) reported the presence of hot ($T > 5 \times 10^8$ K) plasma in this region in the vicinity of the ecliptic plane, which led Axford et al. (1965) to suggest that the magnetotail consists of a north and south lobe, populated by a low density plasma, which are separated by a hot tenuous sheet of plasma. This model was supported by observational evidence from the Explorer XIV spacecraft (Ness, 1965). Further observations of the plasma sheet region made at a distance of $\approx 17 R_E$ from the Earth were reported by Bame et al. (1967). These authors showed that the plasma sheet extends across the midplane of the magnetotail with typical thicknesses of 4 to 6 R_E at this distance. Typical plasma sheet ion and electron temperatures range from 5×10^6 to 5×10^7 K and 2×10^6 to 2×10^7 K respectively, and plasma densities are between 0.1 and 1 cm^{-3} . Within this plasma sheet lies the neutral sheet, the boundary between the magnetotail field lines which leave the Earth (in the south lobe and plasma sheet) and those which return to the Earth (north lobe and plasma sheet). The neutral sheet lies nearly in the ecliptic plane, although, along with the rest of the tail, it may be blown about, or "flap" due to slight changes of direction of the solar wind.

A second important set of field and plasma data was obtained from two brief magnetotail passes by the interplanetary probes Pioneer 7 (in 1966) and Pioneer 8 (in 1968) which passed through the tail at distances of $\approx 1000 R_E$ and $\approx 500 R_E$ respectively. These were the only observations of the distant magnetotail ($X_{gse} < -100 R_E$) available before 1983, and eventual analysis of the data (e.g. Bavassano et al., 1974; Walker et al., 1975) revealed that the distant tail maintained its coherent magnetic structure which was remarkably similar to the near-Earth tail. These observations were however of short duration, presumably due to motion of the tail, such that statistical studies of the properties of the deep tail, or its response to varying geomagnetic activity, were not possible.

4. Current Sheet Stress Balance.

The origin of the tail plasma sheet population can be explained theoretically by considering the motion of particles within the neutral sheet, which has an X-type magnetic field geometry in the presence of reconnection (i.e. with an electric field along the neutral line). This was first described by Dungey (1953), and later investigated by Speiser (1965, 1967, 1968) both analytically and numerically, in the context of the geomagnetic tail. They showed that the

particles accelerated in the current sheets downstream from the neutral line would form approximately field-aligned beams moving along the reconnected field lines away from the neutral line on either side. Considerations of equilibrium and self-consistency were introduced by Alfvén (1968) and Cowley (1973) who considered an antiparallel-field neutral sheet system, and by Rich et al. (1972), Eastwood (1972, 1974) and Hill (1975) who investigated the region downstream from the X-line where a weak field component threads the current sheet.

The field tension in the latter region may be balanced by either a plasma pressure gradient along the current sheet, or by the stress imposed by anisotropic plasma pressure. In the near-Earth region of the geomagnetic tail it is the former factor which is the more important since the system is dominated by the hot, trapped isotropic pressure plasma sheet population which is slowly compressed during earthward transport. Isotropic-pressure models have been developed on this basis by e.g. Bird and Beard (1972) and Birn et al. (1975, 1977). However, in the distant tail, where magnetic mirroring plays little part, pressure gradients will be unimportant and the field tension must instead be balanced by pressure anisotropy, i.e. by the dynamic pressure (in the field line rest frame) of the external (tail lobe) plasma flowing into the central tail current sheet. In this case one-dimensional equilibria can be set up in which variations along the current sheet are ignored compared with those perpendicular to it, the equilibrium condition then being that the plasma outside the current sheet must satisfy the marginal firehose stability condition. Cowley (1980) and Cowley and Southwood (1980) argued that this condition could be applied to systems like the geomagnetic tail in which inflow plasma conditions vary slowly with distance along the current sheet. Although such plasma variations will result in field variations along the current sheet as well, thus violating exact one-dimensionality, the variations perpendicular to the current sheet will remain much more rapid than those along the current sheet, such that the one-dimensional stress balance condition should still be a very good approximation, and can be applied locally. Cowley and Southwood (1980) showed that under these conditions steady states can be set up in which the contraction speed of reconnected field lines away from the neutral line varies with distance in response to slowly changing inflow conditions as determined by local 1-D stress balance.

As indicated by the early works of Dungey and Speiser, the external plasma which flows into the current sheet exits as an approximately field-aligned accelerated beam moving away from the neutral line on the reconnected field lines. Equilibrium considerations show that the beam speed should generally be comparable with the external Alfvén speed, and it is this plasma that corresponds to the accelerated plasma sheet population in the distant tail. Hill (1975) pointed out that due to the finite flow speed of this plasma it would occupy only the central portion (roughly one half) of the wedge of reconnected field lying downstream from the neutral line, and would thus not extend to the magnetic separatrix mapping to the neutral line. However, if energetic, high-speed particles are produced in the current sheet, corresponding to the high-energy tail of the beam population, then these will not be so confined to the central region, but will stream out ahead of the beam to fill the region between the beam edge and the separatrix. Thus in the distant tail the accelerated plasma populations should consist of central jets flowing away from the neutral line at approximately the tail lobe Alfvén speed, with spatially dispersed layers of energetic particles extending outwards from either side of the jet towards the separatrix (e.g. Cowley, 1984).

In the geomagnetic tail this picture should be valid on both sides of the neutral line, but on the Earthward side account must also be taken of magnetic mirroring of the beam particles at the Earth and their subsequent return to the current sheet. The important point here is that due to the continual inflow of the newly-closed flux tubes towards the Earth during the particles' time of flight to the Earth and back, the particles return to the current sheet at a point considerably displaced Earthward from their original current sheet location. Thus the flux tube motion causes the current sheet to be screened from a return flux of mirrored particles for considerable distances downstream from the neutral line, and in this "screened" region the above discussion concerning the applicability of the one-dimensional approximation should apply. In the region containing mirrored fluxes, observations (e.g. Forbes et al., 1981) indicate that the particle distributions become rapidly isotropised, forming the near-Earth, hot, isotropic plasma sheet population for which the 1-D stress balance condition is inappropriate, as discussed above. According to this picture, however, the hot plasma sheet population should possess a layer of Earthward-flowing beam ions at its outer boundaries, together with an energetic particle layer (e.g. Cowley, 1980; Cowley, 1984), as is indeed observed (e.g.

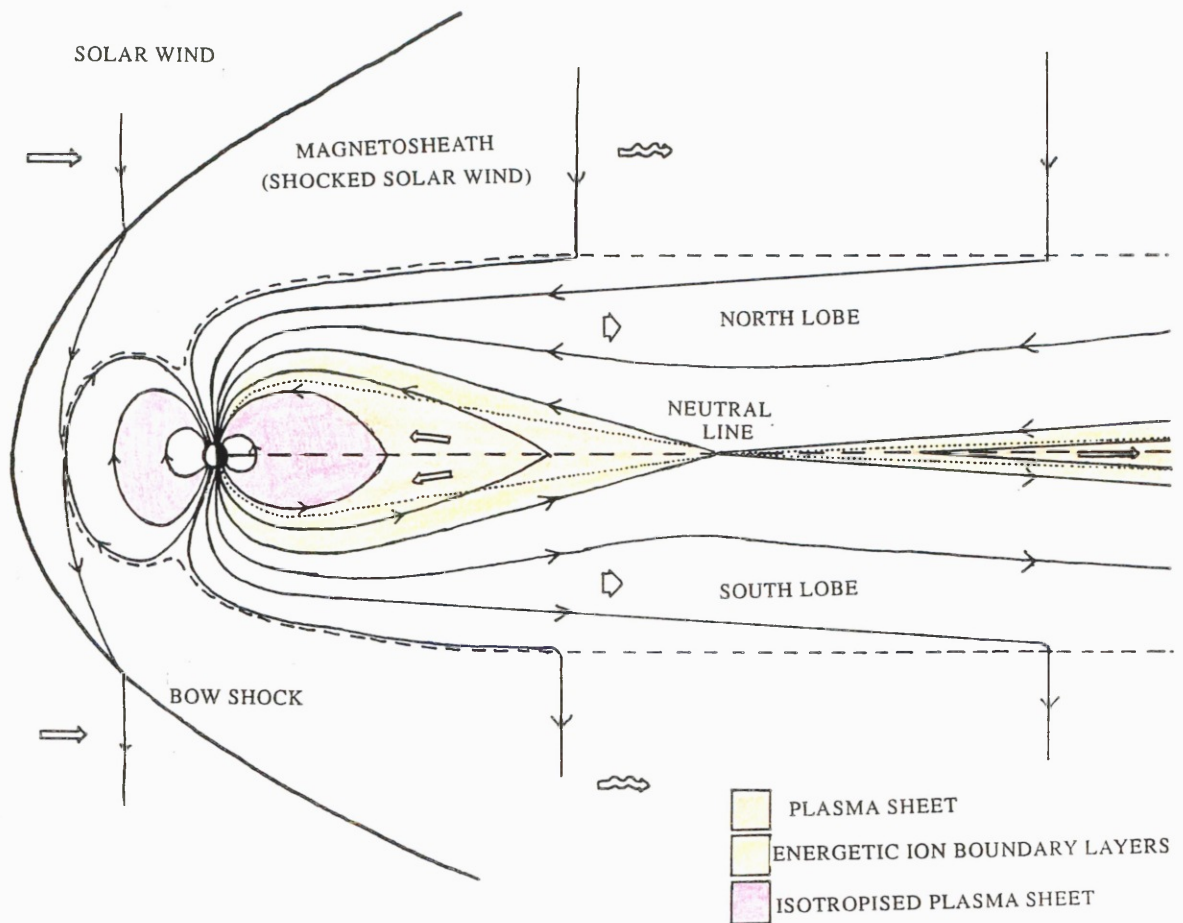


Figure 1.2. Overview of the magnetosphere, indicating the locations of the various regions whose origins are reviewed in this chapter. The bow shock, standing in the solar wind flow upstream from the Earth is shown as the solid line parabola to the left of the diagram. The magnetosheath extends downstream from the shock, and is populated by shocked solar wind particles. This is separated from the magnetosphere itself by the magnetopause, represented by the dashed line in the figure. The solid arrowed lines represent the field within the magnetosphere. On the nightside of the Earth they are drawn back into a long tail structure, as field lines reconnecting into the interplanetary magnetic field (IMF) at the dayside magnetopause are convected tailwards with the solar wind flow. This results in the formation of a structure consisting of two lobes separated by a magnetic neutral sheet (or current sheet), represented by the horizontal dashed line. Magnetic flux is returned to the Earth by reconnection at a neutral line located in the deep tail, and results in the acceleration of particles along the field lines forming the plasma sheet (shown orange) and energetic ion boundary layers (shown yellow). The open arrows indicate the direction of plasma flow. The plasma sheet occupies approximately half of the reconnected field wedge on either side of the neutral line, although the energetic particles may fill essentially all of this region to form the plasma sheet boundary layer. Particle mirroring close to the Earth results in an isotropised plasma sheet region in the near-Earth tail.

Decoster and Frank, 1979; Williams, 1981). In addition, Lyons and Speiser (1982, 1984) have shown that the observed ion distributions in these beams are compatible with expectations based on current sheet acceleration.

The field and plasma flow configurations whose origin we have discussed above are, by way of summary, sketched in Figure 1.2, giving an overview of the magnetosphere and the regions which have so far been discussed in this chapter. Concentrating on the tail region, the black arrowed lines represent the magnetic field, and the white arrows indicate the direction of the plasma flow. The magnetic flux tubes in the lobes convect towards the midplane of the tail, where they reconnect at the neutral line and form the X-type field geometry. The release of magnetic energy in the flux tubes as they contract away from the neutral line accelerates the plasma on them into two beams earthward and tailward along the midplane to form the plasma sheet. The field lines in the plasma sheet on the earthward side have a closed topology, with both ends connected to the Earth. As these field lines contract the plasma trapped on them becomes isotropised, and forms the subsonic plasma sheet close to the Earth. The tailward plasma sheet however is located on interplanetary field lines (both ends in the solar wind), and retains its beam like nature out into the solar wind.

5. Magnetospheric Substorms.

The continual flow of the solar wind around the magnetosphere, and the interaction with it through the processes of dayside reconnection, results in the deposition of solar wind energy into the magnetosphere. The amount of energy deposited depends on the efficiency of the interaction, which in turn depends on the orientation of the IMF to the geomagnetic field. However, for periods of southward IMF, when conditions for dayside reconnection are most favourable, the input of energy into the magnetosphere may exceed 10^{12} watts (Akasofu, 1981). Some of this solar wind energy may be dissipated in the near-Earth region of space by means of Joule heating by ionospheric currents, particle precipitation into the polar regions or by particle injection into the ring current. However much of this energy is effectively stored in the tail magnetic field. During periods of enhanced geomagnetic activity, when the IMF is observed to be southward, the addition of magnetic flux to the tail by rapid dayside reconnection, may be considerably faster than the rate of return of flux to the Earth by reconnection in the deep tail. The magnetic flux content of the tail

lobes therefore increases, as observed by Fairfield et al. (1981), and the near-Earth field becomes stronger and more tail-like. This implies a gradual enhancement in the cross tail current separating the two lobes, and a thinning of the tail plasma sheet, which has also been observed (e.g. Lui et al., 1975; Parks et al., 1979; Forbes et al., 1981). This is known as the "growth" phase of a substorm (McPherron, 1970).

Eventually the tail configuration becomes unstable, and a sudden rapid release of the energy stored in the tail occurs, during the substorm "expansion" phase. Hones (1976, 1979) proposed a model for the sequence of events which occurs in the tail during this period. This model, the "Neutral Line", or "Plasmoid" model, has been most successful in ordering many different types of plasma and field observations within the context of a single theoretical framework, and its basic features are depicted in Figure 1.3. This set of diagrams represents a time sequence of the changes which occur in the plasma sheet during the growth, expansion and recovery phases of a substorm, as seen in the GSM x-z plane. Panel 1 depicts the quiescent plasma sheet as it may exist some time before the beginning of the growth phase. The plasma sheet and associated energetic particle boundary layers (shown shaded) are bounded by the field line labelled 5, which is connected to the neutral line N in the deep tail. The closed field lines 1-4, which were reconnected at the deep tail neutral line at some earlier time, are contracting Earthwards, threading the near-Earth plasma sheet. This latter region is supplied by plasma moving from the lobes into the region of the current sheet, where it is then accelerated out along these field lines, close to the tail midplane (white arrows). Plasma which is ejected tailwards of N is threaded by flux tubes which are now connected to the IMF. The open field lines, 6 and 7, are lobe field lines which have one end attached to the Earth.

The plasma sheet configuration at the instant the tail becomes unstable after the addition of magnetic flux to the tail during the growth phase is shown in panel 2. Schindler (1974) showed that as the plasma sheet thins and the tail field becomes stretched out, the tail approaches a condition of instability to the ion tearing mode. This results in the formation of a substorm neutral line N' extending for some distance across the Earthward, near midnight section of the plasma sheet, and the beginning of reconnection of closed field lines at this point. This commencement of near-Earth ($r \approx 10-15 R_E$) reconnection marks the onset of the substorm expansion phase, which may be evidenced at the Earth by sudden auroral brightening, occurrence of Pi2 pulsations, and sharp depressions

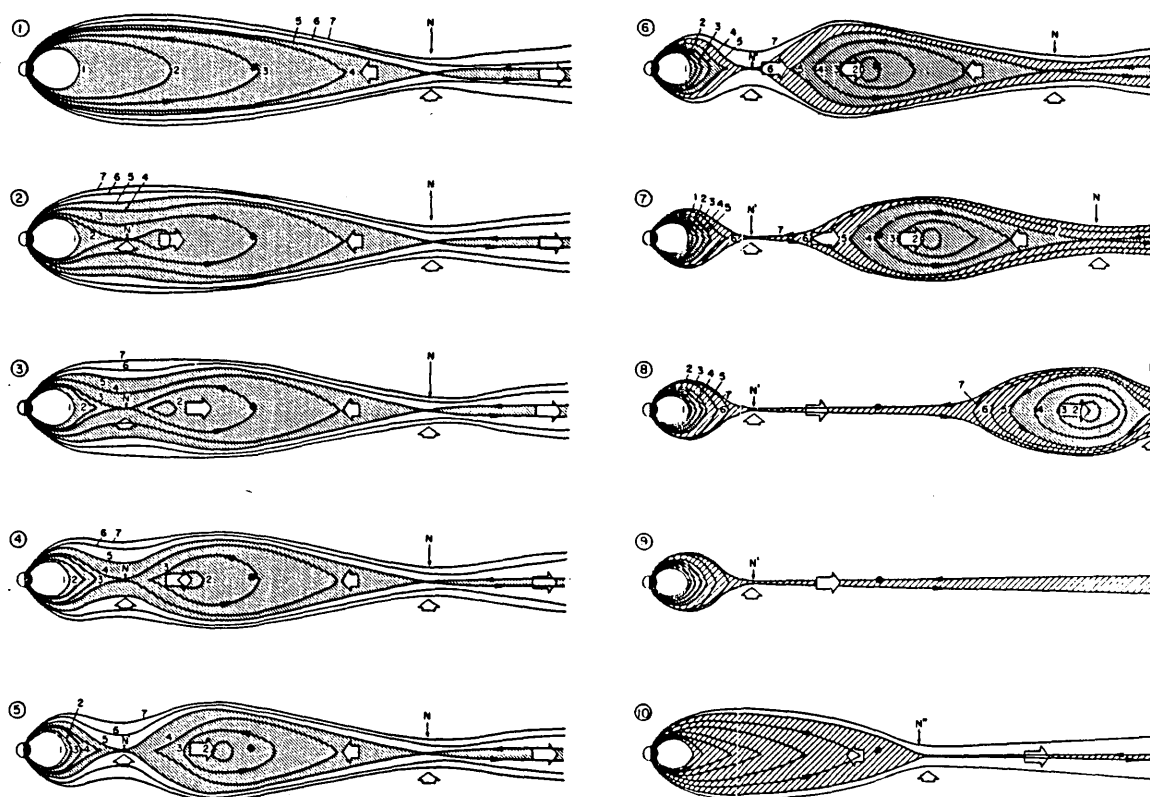


Figure 1.3. Plasma sheet configuration changes during a substorm according to the neutral line model of substorms. The solid arrowed lines represent the field lines near the tail centre plane, whilst N indicates the position of the presubstorm neutral line. The regions of fine hatching represent the regions occupied by plasma from the presubstorm plasma sheet, and the open arrows depict the plasma flow direction and relative speed. At substorm onset (panel 2) a new neutral line forms at position N', much closer to the Earth. Continuous rapid reconnection (panels 3,4) at this new neutral line eventually pinches off the old plasma sheet (panel 5), resulting in the formation of a closed loop plasmoid structure, which then moves down the tail (panels 6,7,8). The regions of coarse hatching designate plasma that is brought in with the reconnecting lobe field lines to form the post plasmoid plasma sheet (panel 9). After some time in the near Earth region the neutral line retreats tailwards during substorm recovery (N'' in panel 10), until a quiet time configuration (panel 1) is again achieved. (After Hones, 1980)

of the auroral zone field strength. The consequence of this reconnection is the formation of closed loops of magnetic flux within the plasma sheet tailwards of N' (panels 3 and 4), which are carried tailwards with plasma jetting away from the new neutral line. The eventual reconnection of line 5, which bounds the plasma sheet region, results in a complete severance of the plasma sheet region tailward of N' from the Earth, which is now free to flow tailwards under the influence of a plasma pressure gradient which is no longer balanced by magnetic tension. This closed loop structure, and the plasma trapped on it is known as a "plasmoid". Note the plasmoid contains a O-type magnetic neutral line, which separates regions of the plasmoid with a northward component of the field (tailward of the O-line) from regions with a southward component (Earthward of the O-line). Further reconnection at N' results in the connection of lobe field lines (panels 6-9). The region occupied by these reconnected lobe field lines, and the plasma which is subsequently accelerated tailwards of N' is shown hatched in these diagrams. In the meantime the plasmoid is moving rapidly tailwards along the tail centre plane, and is eventually ejected back into the solar wind. The elapsed time between panels 2 and 8 is of order 10 minutes.

The departure of the plasmoid leaves a very thin plasma sheet tailwards of N' (panel 9), in which plasma flows rapidly tailward. This region is threaded by field lines with a southward component, which are connected at both ends to the IMF.

The final panel (10) of Figure 1.3 depicts what is known as the recovery phase of the substorm. Some time after the expansion phase onset (typically 30-90 minutes), the substorm neutral line moves quite rapidly tailwards. As it does so the plasma jetting Earthwards of this neutral line, threaded by newly reconnected closed field lines (with northward field component), replenishes the near-Earth plasma sheet, causing it to increase in thickness as well as length. The structure of the plasma sheet thus returns eventually to the quiescent formation shown in panel 1.

This neutral line model for substorms received considerable observational support even before the ISEE-3 geotail mission, which is discussed below. For example, Nishida and Nagayama (1973) showed, in a study of many substorms, that the plasma sheet field between 25 and 35 R_E downtail had a southward component almost without fail near the onset of strong substorms, indicating

the presence of a reconnecting neutral line Earthward of these positions. Also, Hones (1976) presented evidence for tailward flows of plasma at 30 R_E downtail almost immediately after substorm onset, again indicating the presence of a near-Earth neutral line. Further, this paper also interprets short duration encounters with the plasma sheet as evidence for the thin plasma sheet after departure of the plasmoid. Similar near-Earth observations, relating to the release of a plasmoid and the subsequent formation of a thin tailward post-plasmoid plasma sheet, have also been presented by Coroniti et al. (1980), Fairfield et al. (1981), and Beiber et al. (1982).

Other models of tail dynamics during substorms (e.g. Chao et al., 1977; Rostoker and Eastman, 1987) have been presented. However, the ISEE-3 geotail mission provided further evidence for the neutral line model (including direct observations of plasmoids), such that it has now become very widely accepted amongst workers in this field. These, and other, results from this mission are reviewed in the next section.

6. The ISEE-3 Deep Tail Mission.

In late 1982 the International Sun-Earth Explorer 3 (ISEE-3) spacecraft, which for the previous 5 years had been acting as a solar wind-monitoring satellite upstream from the Earth, began a series of orbital manoeuvres which eventually resulted in its encounter with comet Giacobini-Zinner in September 1984. During these manoeuvres the spacecraft spent several extended periods on the nightside of the Earth at distances of between 60 and 240 R_E. As a result the spacecraft provided the first prolonged observations of the magnetic tail at these trans-lunar distances. Early results confirmed the previous picture of twin lobes (e.g. Slavin et al., 1983), and the existence of plasma regimes recognizable as the mantle and plasma sheet (Bame et al., 1983; Zwickl et al., 1984). Cowley et al. (1984) and Richardson and Cowley (1985) investigated the energetic ion ($E > 35$ keV) regimes in the deep tail, and found the plasma sheet to be a region of enhanced fluxes of these ions, which are usually flowing unidirectionally tailward. These fluxes often extend outside the plasma sheet boundary and form a plasma sheet boundary layer. These observations are generally compatible with the theoretical picture of rapidly flowing plasma jets and surrounding energetic particle layers.

Observations of the various plasma regimes are found to be more intermittent in the deep tail than in the near-Earth region as there is considerable lateral movement of the tail at these distances (Hones et al., 1984b). However, this motion, together with the extended durations of the spacecraft's stay in this region, enabled a number of statistical studies to be made. Slavin et al. (1985) determine the East-West extent of the tail to be $60 \pm 5 R_E$, whilst Sibeck et al. (1985, 1986) have shown that the tail is subjected to a flattening effect in the North-South direction, due to effects associated with IMF B_y , such that the typical extent of the tail in this direction is somewhat less than $60 R_E$.

The ISEE-3 mission lead to a number of advances in our knowledge of the average quiet time structure of the magnetotail when the level of geomagnetic activity is very low. Tsurutani et al. (1987) showed that the average lobe field strength at distances greater than $200 R_E$ downtail is 7.1 nT during such periods (cf. average field strengths of 9.2 nT for all geomagnetic conditions, reported by Slavin et al., 1985). The position of the quiet time neutral line within the deep tail has been estimated by several authors using different techniques (e.g. Baker et al., 1984; Scholer et al., 1984; Zwickl et al., 1984). Although the position is quite variable, it appears that the neutral line is on average $120 R_E$ downtail from the Earth. However, Slavin et al. (1985) also studied the variation of field and plasma parameters across the magnetotail and concluded that the quiet time neutral line is, in fact, curved away from the Earth, lying at about $120 R_E$ in the centre of the tail, and much further tailwards on the flanks.

Several studies of the deep tail data concentrated on the effect of the y- (East-West) component of the IMF on the tail. Sibeck et al. (1985) showed in a study of deep tail magnetopause crossings that the tail can become twisted. The sense of the twist is dependent on the direction of IMF B_y , as was predicted by Cowley (1981). Gosling (1984) and Gosling et al. (1984, 1985) studied the plasma conditions in the tail lobes. These studies showed that the distribution of plasma in the lobes is asymmetric, and that this also depends on the sign of IMF B_y . This is illustrated in Figure 1.4, showing a cross section of the distant magnetotail, for IMF B_y positive. The y-component of the field results in the preferential addition of flux (recently reconnected on the dayside of the Earth) and plasma to the dawn side of the northern lobe, and the dusk side of the southern lobe, thus creating density gradients across and between the lobes. The entry of plasma into the lobes is, however, in qualitative agreement with the leaky magnetopause model of Pilipp and Morfill (1978),

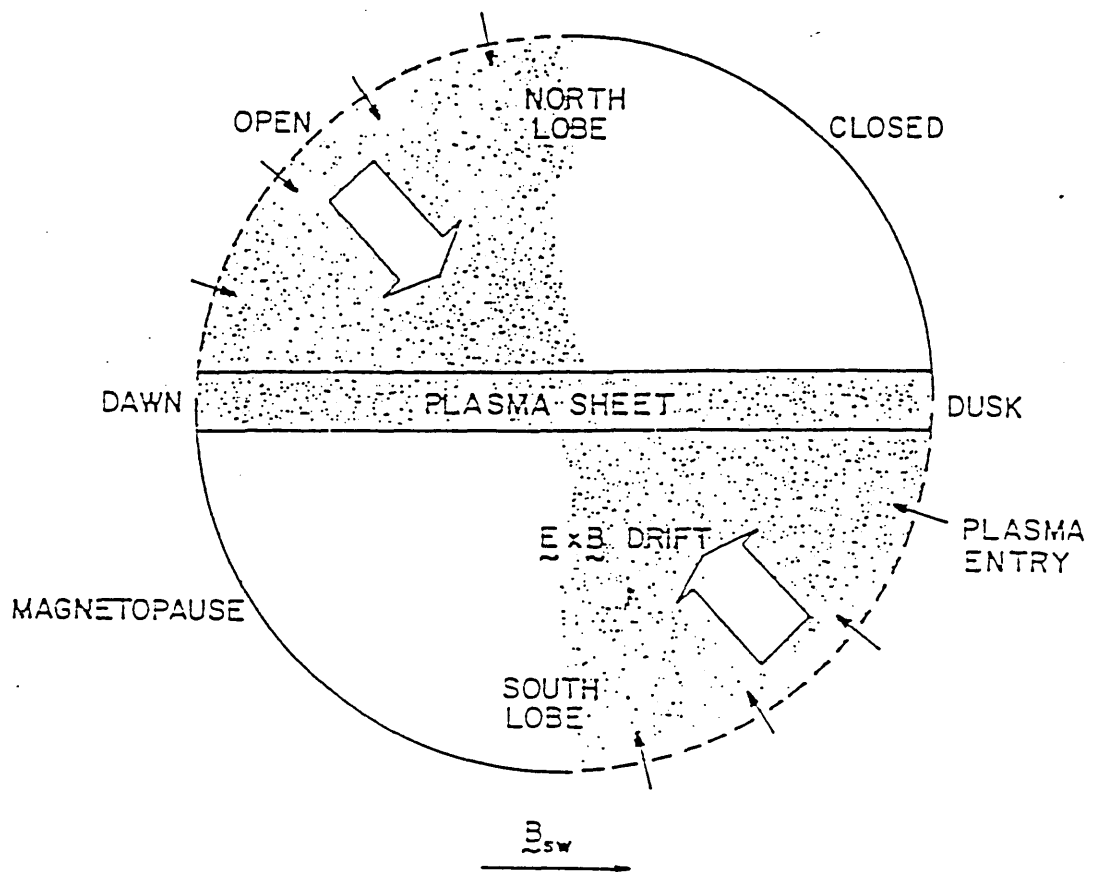


Figure 1.4 Cross-sectional view, looking tailward from the Earth, of the distant geomagnetic tail illustrating plasma entry into the tail for a positive y-component of the interplanetary magnetic field. Magnetic flux reconnected at the dayside magnetopause, and associated plasma, is added preferentially to the dawn side of the northern lobe and the dusk side of the southern lobe in this case. This results in a plasma density gradient across and between the two lobes, and simultaneous flow shears are also expected to occur. (After Gosling et al., 1985)

which requires continuous solar wind particle entry over the entire length of the magnetopause (Slavin et al., 1985). Energetic particle conditions in the tail lobe were reported briefly by Cowley et al. (1984), who reported that the energetic ion pitch angle distribution was peaked closely perpendicularly to the field direction. However, spatial variations in the properties of these particles have yet to be studied in detail.

Finally, much work has been done in the past 5 years on the relationship between the structure of the magnetotail and geomagnetic activity, particularly its response to substorms. The ISEE-3 deep tail data sets provide strong support for the neutral line model of substorms, most notably through direct observations of plasmoid structures. The properties of these structures, and the effect their passage on the rest of the tail has been discussed by many authors (e.g. Hones et al., 1984; Scholer et al., 1984; Slavin et al., 1984; Richardson and Cowley, 1985; Richardson et al., 1987). These studies revealed the average length of plasmoids to be about 80 R_E , although they can be between 50 and 100 R_E , and are also observed as multiple loop structures. The downtail propagation speed may be between 300 and 1000 km s^{-1} , and their arrival in the deep tail at some 30 minutes or so after substorm expansion phase onset (as determined by Earth bound systems) is in qualitative agreement with their travel time from the near-Earth region. The passage of a plasmoid past the spacecraft location is marked by a northward then southward deflection of the tail field. If the spacecraft enters the plasmoid structure itself, particle populations with magnetically trapped characteristics may be observed. However, evidence for the passage of a plasmoid past the spacecraft location, without a direct encounter, can be obtained from the compression of the tail lobe field which occurs as the plasmoid passes. Such compressions have been termed "Travelling Compression Regions" (Slavin et al., 1984).

7. Summary.

Work done over the past two or three decades has lead to a picture of the interaction between the solar wind and terrestrial magnetic field in which magnetospheric convection is largely driven by reconnection (either continuous or intermittent) at both the dayside magnetopause and in the geomagnetic tail. The magnetotail, formed by this interaction, is observed to be a twin lobed structure, extending at least 1000 R_E downstream from the Earth. The lobes are separated by a neutral sheet and an energetic plasma population, which, in

periods of limited geomagnetic activity, is a result of reconnection at a neutral line located some 100 R_E downstream. The dynamics of the tail at times of more enhanced geomagnetic conditions can be most successfully explained in terms of the neutral line model of substorms, involving the formation of a new neutral line close to the Earth, and the ejection downtail of a closed magnetic loop plasmoid structure.

In this thesis we discuss a number of different aspects of field and particle characteristics in the deep tail. In the next chapter we show how the previous equilibrium models of steady state reconnection in the geomagnetic tail, set up using local one dimensional stress balance conditions (as discussed in Section 4) can be readily generalised to include the effect of time dependence, both in terms of time-dependent reconnection rates and motion of the neutral line itself. The results are illustrated by showing how the structure of the plasma sheet in the geomagnetic tail is expected to behave during a substorm, using reconnection rates and neutral line motions which are expected from the neutral line model, and parameters which are deduced from observation. The results are further tested in the following chapter (Chapter 3) in which we present a case study of a substorm event using data from ISEE-3 in the deep tail in conjunction with other, near-Earth data sets which allow the events in the tail to be related to the prevailing geomagnetic conditions. We relate these events in the tail to those predicted by the theory of the previous chapter, and demonstrate a quantitative agreement between the two. The event thus lends further support to the neutral line model of substorms.

In Chapter 4 we return briefly to considerations of stress balance in the tail plasma sheet. Previous models of current sheet equilibrium in the geomagnetic tail based on the one-dimensional field approximation have assumed symmetrical inflow plasma conditions in the two tail lobes. However, as discussed above, large asymmetries in density have been observed in the tail lobes due to effects controlled by IMF B_y , and simultaneous flow shears are also expected from theory. It is shown that the current sheet equilibrium condition can be readily generalized to include lobe plasma asymmetry under the simplifying assumption that all particles incident on the current sheet are transmitted through it. The result is expressed in a form which emphasizes the physical equivalence of stress balance by anisotropic plasma pressure and by net flow through the current sheet. The former case occurs for symmetrical lobe conditions and balance is expressed in terms of the marginal firehose

stability condition. The latter case occurs if one lobe dominates, when the field-aligned plasma flow speed in the field line rest frame must equal the tail lobe Alfvén speed. Results are illustrated by a simple example in which the inflow plasmas are approximated as cold ion beams of unequal density and speed. It is shown that equilibrium solutions cease to exist for sufficiently large inflow velocity shears, but that in practice this condition is most unlikely to be encountered in the tail.

In Chapter 5 we discuss the characteristics of energetic ion regimes in the tail lobes. The pitch angle distribution of such ions is shown to be peaked closely perpendicular to the magnetic field direction. We discuss the source of such ions, and produce a model which successfully explains the nature of the pitch angle distribution. This model is based on particle entry to the lobes through an open magnetopause boundary, with a spatially varying source in the magnetosheath. By considering the motion of the particles within the lobes, pitch angle distributions can be produced from the model which agree quantitatively with those observed. The spatial dependence of these theoretically produced pitch angle distributions is discussed, although observationally this has yet to be considered in detail.

Finally, in Chapter 6, we summarise the achievements of the work that is presented in this thesis, and briefly discuss its applicability and the options for its further development.

CHAPTER 2

SIMPLE MODELS OF TIME-DEPENDENT RECONNECTION IN A COLLISION- FREE PLASMA WITH AN APPLICATION TO SUBSTORMS IN THE GEOMAGNETIC TAIL.

(1) Introduction

A basic understanding of the structure and properties of the accelerated plasma populations in the geomagnetic tail can be derived from the models of steady state reconnection and current sheet stress balance that were discussed in the introduction to this thesis, and these give a good initial framework to relate to observations. However, during substorms major changes occur in the tail, which are believed to involve variations in the reconnection rate and motions of the neutral line, which were also discussed in the introduction (cf. the neutral line model of substorms). In this chapter we will show how the theoretical models based on the 1-D equilibrium approximation can be generalised to include these effects.

For simplicity we will neglect spatial variations in the properties of the inflow plasma, but in principle these could be incorporated following the methods of Cowley and Southwood (1980). It should be noted that as in the steady state models, the theory developed here is not valid in the immediate vicinity of the neutral line where the 1-D approximation necessarily breaks down, and in the near earth regime where mirrored particles must be taken into account. It should also be stressed from the outset that the theory does not determine the reconnection rate or the neutral line motion, or their variations in time. Rather these are taken to be given (determined for example by the external boundary conditions), and the theory then seeks to show how the structure of the accelerated particle populations and the energetic particle boundary layers vary in response. In the next section we will briefly review some relevant aspects of the steady state theory, and introduce a new method of determining the beam and energetic particle layer structure, a method that is readily generalised to the time dependent case. In Section 3 we will investigate the effect of a time varying reconnection rate (parameterised in terms of the electric field along the neutral line) on the plasma sheet structure, whilst in Section 4 neutral line motion will be considered, firstly for a steady reconnection rate, and then for time dependent reconnection, the latter giving a completely general picture for any variations in the conditions at the neutral line. Finally, in Section 5 we illustrate our results by considering the plasma sheet variations which occur in the geomagnetic tail during substorms, using time dependent reconnection rates and neutral line motions suggested by observation. Specifically, for definiteness, we concentrate on variations in the more distant tail, as recently investigated by the ISEE-3 spacecraft (e.g. Tsurutani and von Rosenvinge,

1984). This will also allow direct comparison with data from ISEE-3, and in the next chapter we shall present a case study of a substorm event to further illustrate the scope of this theory.

(2) Steady-State Reconnection

In this section we will first briefly review the steady state reconnection problem based on the 1-D current sheet equilibrium conditions before considering the time dependent effects of varying reconnection rates and neutral line motion in Sections 3 and 4. We note that the 1-D picture clearly breaks down in the vicinity of the neutral line itself, and this region is not treated explicitly in this thesis. Rather, we assume that the field threading the current sheet increases rapidly away from the neutral line to values determined by the 1-D stress balance as discussed by Cowley and Southwood (1980). Since this should occur on spatial scales comparable to a few ion gyroradii, the region not covered by the theory represents only a small proportion of the current sheet system, and is treated in the following simply as a discontinuity between the regions Earthward and tailward of the neutral line.

The steady state model assumes a symmetrical inflow of plasma from the lobes on either side of the current sheet and 1-D fields varying only in the direction z normal to the current sheet (usual magnetospheric coordinates are used with the X -axis aligned with the earth-sun line, the Y -axis towards dusk, and parallel to the cross tail current, and the Z -axis pointing northwards). The fields of the current sheet system are then of the form

$$\begin{aligned} \mathbf{E} &= (0, E_y, E_z(z)) \\ \mathbf{B} &= (B_x(z), 0, B_z) \end{aligned} \tag{2.1}$$

where B_z, E_y are constant, as illustrated in Figure 2.1 (i). This figure shows the form of the magnetic field which we are considering, in which B_x reverses across a thin current layer in the presence of a small B_z component, such that the field lines consist of sharply-bent hairpins. Now it is possible to transform into a frame moving along the current sheet in which the value of the cross tail electric field E_y vanishes (de Hoffman and Teller (1950), Speiser (1965), Eastwood (1972)). This frame moves away from the neutral line in the x -direction at a speed

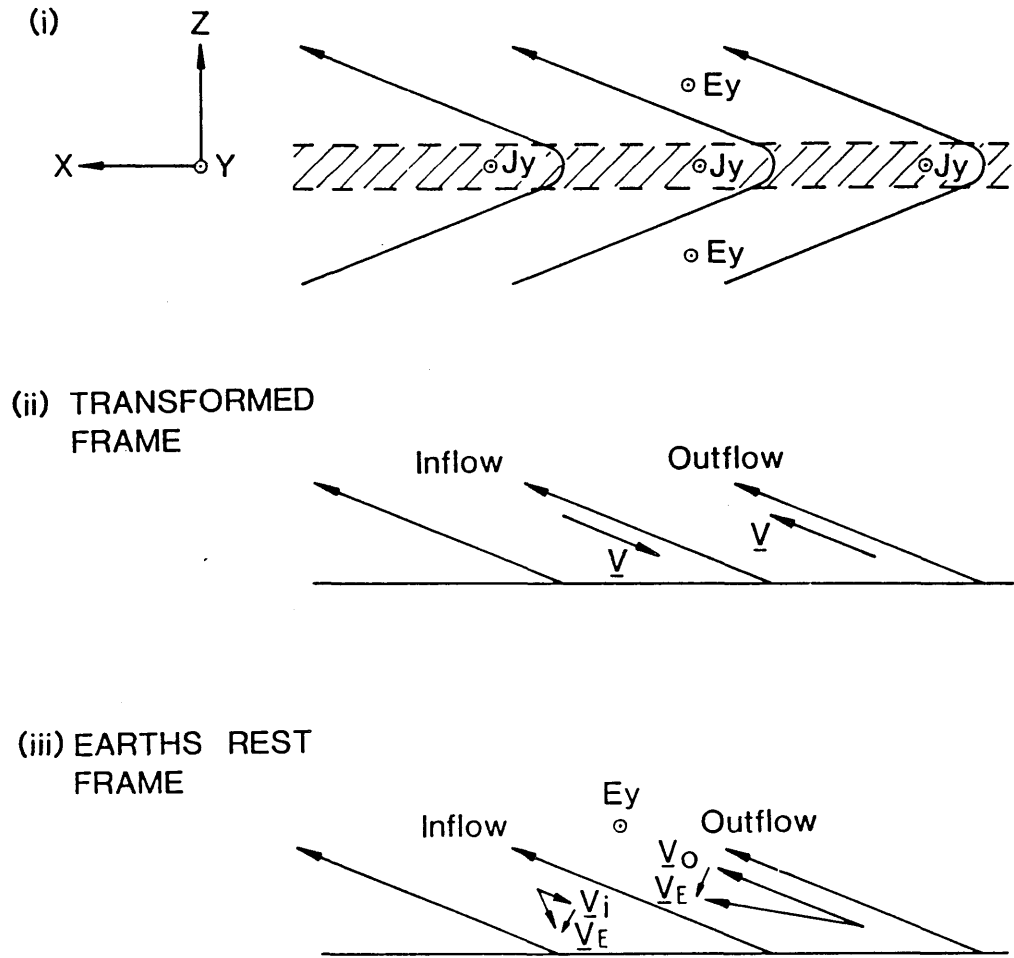


Figure 2.1. (i) Sketch of the fields of the 1-D current sheet, together with the coordinate system employed. The x-component of the magnetic field (solid arrowed lines) reverses across a thin current sheet (hatched region) in which current J_y flows parallel to the constant cross tail electric field E_y . In the theory we assume $|B_x| \gg |B_z|$ outside the current sheet resulting in sharply bent hairpin-like field lines. (ii) Plasma flow in the frame in which the electric field has been transformed away. In this frame particles move into and out of the current sheet by field aligned flow since there is no $\mathbf{E} \times \mathbf{B}$ drift. In the absence of E_y the particles also experience no change in speed in their interaction with the current sheet. (iii) The equivalent flows in the earth's (and neutral lines') rest frame, moving with a speed v_F to the right relative to the above diagram. The flows in this frame can be considered as consisting of modified field-aligned components v_i and v_o together with an $\mathbf{E} \times \mathbf{B}$ drift speed v_E perpendicular to the field.

$$v_F = \frac{E_y}{B_z} , \quad (2.2)$$

which is just the $\mathbf{E} \times \mathbf{B}$ drift speed at the centre of the current sheet (where $B_x = 0$).

In this frame the particles move into and out of the current sheet by field aligned flow due to the absence of $\mathbf{E} \times \mathbf{B}$ drifts, and the speed of the particles is unchanged by their encounter with the sheet, as there is no accelerating electric field. The particles therefore simply stream into and out of the current sheet along the field without change of speed as shown in Figure 1(ii), and in equilibrium the field tension is then balanced by the reversal in their X-direction of motion. Rich et al. (1972) showed that in equilibrium the plasma outside the current sheet must satisfy the marginal firehose stability condition, given by

$$P_{\parallel} - P_{\perp} = \frac{B^2}{\mu_0} , \quad (2.3)$$

where $P_{\parallel}$ and $P_{\perp}$ are the components of the plasma pressure tensor parallel and perpendicular to the field lines respectively, and B is the magnetic field strength outside the current sheet. If the inflow plasma is taken to be a cold field-aligned ion beam of density n and speed v , and if it is also assumed that the outflowing plasma also remains field aligned (with the same density and speed) then equation (2.3) becomes

$$2nm_i v^2 = \frac{B^2}{\mu_0} , \quad (2.4)$$

where m_i is the ion mass, the electron mass having been neglected. Thus in the transformed frame the equilibrium condition is that the field-aligned beam speed should be given by

$$v = \frac{B}{\sqrt{2\mu_0 n m_i}} = \frac{V_A'}{\sqrt{2}} = V_A , \quad (2.5)$$

where V_A' is the Alfvén speed in the tail lobe, and V_A is the Alfvén speed just outside the current sheet, where the density is $2n$ due to the simultaneous presence of the inflowing and outflowing plasma beams. It should be noted that if B_z is small compared with B_x outside the current sheet (as will be

assumed throughout this chapter, and as will generally be the case provided the reconnection rate is not too large as we will show below), then the field-aligned motion outside the current sheet in the transformed frame given by equation (2.5) will be mainly along the X-axis, as can be seen in Figure 2.1 (ii) (the inflow being in the -ve x direction Earthward of the neutral line and in the +ve x direction tailward of the neutral line).

We now transform back to the Earth's (the neutral line's) rest frame, and assume that in this frame the plasma is flowing down-tail (-ve x direction) with a speed v_i (corresponding to the down-tail flow of the lobe plasma). Again, this velocity will be mainly along the x-axis for $|B_z| \ll |B_x|$ outside the current sheet. In this frame the particles also experience an $\mathbf{E} \times \mathbf{B}$ drift, which is mainly in the z direction, towards the current sheet (see Figure 2.1(iii)). Let us consider for definiteness the Earthward side of the neutral line. In the transformed frame the particles move into (-x direction) and out of (+x direction) the current sheet with speed $v = V_A$ given by equation (2.5), while in the Earth's frame the field-aligned inflow speed (-x direction) is v_i by hypothesis. Thus in equilibrium the transformation speed must be (+ve in the +x direction)

$$v_{FE} = \frac{E_y}{B_z E} = V_A - v_i \quad , \quad (2.6a)$$

thus giving the speed with which the reconnected field lines contract away from the neutral line, while the speed of the outflow plasma (again +ve in the +x direction) is

$$v_{OE} = 2V_A - v_i \quad . \quad (2.6b)$$

In these expressions the subscript E refers to the Earthward side of the neutral line. It should be stressed that the equilibrium condition determines the contraction speed of the reconnected field lines (and hence the outflow beam speed) in the Earth's frame. It does not determine the rate of reconnection, i.e. the value of E_y . For a given E_y value the equilibrium condition (equation 2.6a) determines the flux threading the current sheet ($B_z E$), and as the reconnection rate (E_y) increases so does this flux, in direct proportion. This result can be viewed as a simple consequence of flux conservation, since Faraday's law shows that E_y is just the quantity of flux reconnected per unit length of the

neutral line per unit time, while the contraction rate of the flux tubes along the current sheet away from the neutral line is independent of E_y . Thus as E_y increases, B_z also increases. Thus also the angle of the field lines to the current sheet and the width of the wedge of reconnected field lines increase. The $|B_z| \ll |B_x|$ approximation used here becomes invalid when the reconnection rate is so large that the plasma inflow speed towards the current sheet ($\approx E_y/B$) approaches the tail lobe Alfvén speed. We are generally interested in much smaller values than this so that the conditions for validity of the approximation should be well satisfied. In principle, however, the calculation could be generalised to arbitrary reconnection rates and inflow speeds (e.g. Cowley, 1980), but at the expense of increased complexity.

Turning now to the region tailward of the neutral line (subscript T), arguments completely analogous to those employed above show that the field line contraction speed away from the neutral line is

$$v_{FT} = \frac{E_y}{B_{zT}} = V_A + v_i \quad (2.7a)$$

while the outflow beam speed is

$$v_{OT} = 2V_A + v_i \quad (2.7b)$$

(both quantities being +ve in the -ve x direction). Comparison of equations (2.6) and (2.7) shows that for v_i positive (down-tail flow in the -ve x direction), the field lines and the outflow plasma flow away faster on the tailward side of the neutral line than on the Earthward side. Since E_y is constant and uniform for a 2-D steady state this implies that $|B_z|$ is larger on the Earthward side of the neutral line than on the tailward side, so that the wedge of reconnected field is similarly asymmetric.

We thus now consider the spatial structure of the reconnected field wedge and its associated accelerated particle populations, this being the main topic of this chapter. We first calculate the thickness of the wedge of reconnected flux at position X along the current sheet, at distance $|X - X_N|$ from the neutral line located at X_N . Assuming that X is sufficiently far from the neutral line that the small region surrounding the latter where our theory does not apply may be

ignored, the flux threading the current sheet per unit length in the y-direction between X and the neutral line is

$$\Phi = |B_z| \cdot |X - X_N| = \frac{E_y |X - X_N|}{v_F} \quad (2.8)$$

It should be noted that this flux can be regarded as the total amount of magnetic flux reconnected (at rate E_y) in the time taken for the reconnected flux tubes to travel along the current sheet from the neutral line to X (a time $|X - X_N|/v_F$). If we now further assume that the field strength in the reconnected field wedge outside the current sheet is nearly the same as the lobe field strength B (thus neglecting the diamagnetic effect of the accelerated plasma, consistent with our assumption that the outflow plasma remains a cold, field aligned beam in the transformed frame) then the half-width W of the wedge (i.e. the perpendicular distance from the current sheet to the separatrix) is given by flux conservation as

$$BW(X) = \Phi = \frac{E_y |X - X_N|}{v_F}$$

or

$$W(X) = \frac{E_y |X - X_N|}{B v_F} \quad (2.9)$$

where v_F is given by equations (2.6a) and (2.7a) on the earthward and tailward sides of the neutral line respectively. Note that W increases linearly with distance from the neutral line giving a narrow wedge (for $|B_z| \ll B$), and that the opening angle of this wedge is linearly proportional to the reconnection rate E_y as previously anticipated.

We now calculate the region within this wedge which is occupied by particles originating from the current sheet which flow out along the reconnected field lines with a general field-aligned speed v_p (larger than v_F). Since we assume that the whole of the current sheet acts as a source of these particles, the outer boundary of this particle region corresponds to the trajectory which maps back to the vicinity of the neutral line. In a steady state this boundary can be calculated by considering the angle of the reconnected field lines to the current sheet and the angle of the trajectories to these field lines (determined by v_p and

the $\mathbf{E} \times \mathbf{B}$ drift, e.g. Cowley, 1984). However, here we will introduce an alternative method which is more readily generalised to the time-dependent cases to be considered in subsequent sections. The basis of the calculation may be understood by noting that since the boundary particle is emitted from the neutral line vicinity, the region between the separatrix and the particle boundary at a given distance from the neutral line just contains the magnetic flux which has been reconnected during the time taken by the particle to reach that distance from the neutral line. Thus the perpendicular distance D from the particle boundary to the separatrix at distance $|X - X_N|$ from the neutral line is given by

$$D = \frac{E_y}{B v_p} |X - X_N|. \quad (2.10)$$

Thus, subtracting this from the half thickness of the reconnected field wedge W we have the half-thickness S of the particle layer of speed v_p given by

$$S = W - D = \frac{E_y}{B} |X - X_N| \left(\frac{1}{v_F} - \frac{1}{v_p} \right). \quad (2.11)$$

For the special cases of the accelerated beam particles (plasma sheet particles) whose speeds are given by equations (2.6a) and (2.6b) we have

$$S_E = \frac{E_y}{B} |X - X_N| \cdot \frac{V_A}{(V_A - v_i)(2V_A - v_i)} = W_E \cdot \frac{V_A}{(2V_A - v_i)} \quad (2.12a)$$

and

$$S_T = \frac{E_y}{B} |X - X_N| \cdot \frac{V_A}{(V_A + v_i)(2V_A + v_i)} = W_T \cdot \frac{V_A}{(2V_A + v_i)} \quad (2.12b)$$

Note that if $v_i = 0$ (the symmetrical case in which the inflow plasma has no field-aligned flow) then the ion beam occupies just half of the reconnected field wedge. For v_i positive (down-tail flow) the wedge will be wider on the Earthward side of the neutral line and narrower on the tailward side, while the plasma sheet beam will occupy somewhat more than half this wedge on the Earthward side, and somewhat less than half of the wedge on the tailward side. The boundary of particles whose field-aligned speed exceeds the beam speed

will, of course, be found outside the latter as given by equation (2.11). The boundary in the limit of infinite speed is the magnetic separatrix itself.

A typical example is shown in Figure (2.2i), specifically for the case $v_i = 0.3 V_A$, and for a reconnection rate given by $E_y = V_{AB}/4$. (We note that such a large reconnection rate technically violates the assumptions made above, but was used for the sake of clarity of the figure. The figure can be applied to other reconnection rates simply by scaling the vertical axis with respect to the horizontal. Thus for a reconnection rate half of the above, the vertical dimensions should just be halved relative to those shown). In this diagram the horizontal solid line represents the central current sheet, while the arrowed solid lines are the magnetic field lines. The hatched areas bounded by the dashed line correspond to the regions occupied by the plasma beams (the plasma sheet) while the dot-dashed lines show the boundary of higher speed ions, specifically for $v_p = 3V_A$. It may be noted that while the speeds of the plasma beams in the hatched regions (the plasma sheet) on either side of the neutral line are given by equations (2.6b) and (2.7b), the beams coexist in these regions with the lobe inflow plasma which has a down-tail speed v_i . The speed of the combined distribution of inflow and outflow plasma is always wholly in the $\pm x$ direction, and equal to the field line speed v_F , as is obvious from the frame transformation argument employed above.

It should be noted that the assumption inherent in this theory that the whole of the cross tail current flows in a thin quasi-one-dimensional current layer at the centre of the plasma sheet (c.f. Figure (2.2)) is an idealization which is not strictly valid in the geomagnetic tail. In reality part of the energy liberated from the field to the plasma in the current sheet will appear in the form of heat in the outflow plasma, rather than wholly as bulk flow energy along the reconnected field lines as assumed in the "cold beam" approximation used here. Consequently cross-field currents will also flow within the plasma sheet wedge itself, and at its outer surface, which will lead to a diamagnetic depression of the field within the plasma sheet relative to the lobe, consonant with the requirements of pressure balance. These effects may be viewed as being due to a slow mode expansion of the heated plasma along the reconnected field lines, the associated currents then being the counterparts of the slow mode shocks in Petschek's (1964) theory. As a result of the neglect of these effects in the present work the results of our theory will only apply semi-quantitatively to the geomagnetic tail. The justification for their neglect is that the resulting theory

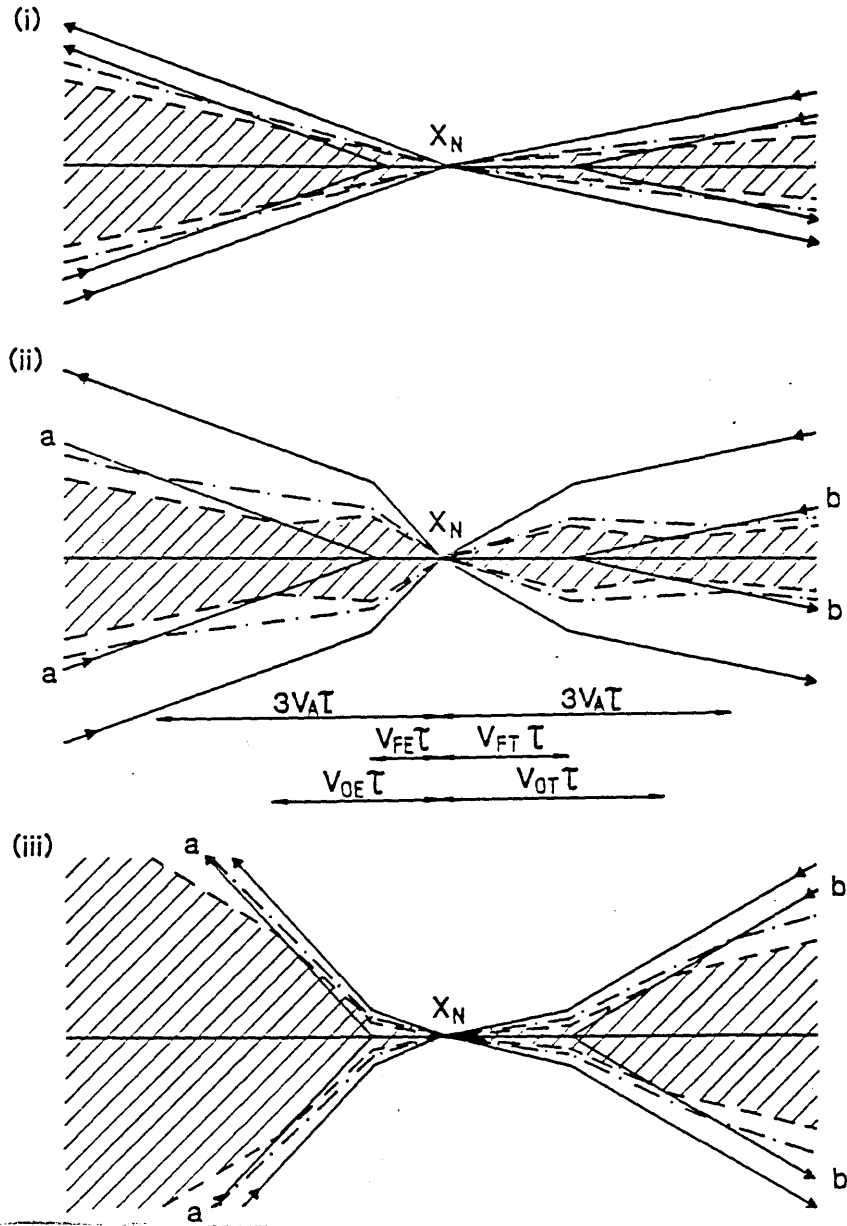


Figure 2.2. (i) Field structure and particle populations resulting from steady state reconnection at a stationary neutral line at X_N , for a lobe flow speed $0.3 V_A$ (left to right), and reconnection rate of $E_y = V_{AB}/4$ (although by scaling the vertical axis with respect to the horizontal the diagram could be made representative of any other reconnection rate, e.g. for reconnection rate one quarter of the above, the vertical scale should be decreased by a factor of 4). The reconnected field is represented by the arrowed solid lines, the plasma sheet by the hatched region bounded by the dashed lines, and the boundary of energetic particles of speed $3V_A$ by the dot-dashed lines. (ii) Configuration at time τ after reconnection has suddenly increased by a factor of 3 from the situation in (i). The last field lines reconnected before the change occurred are marked a-a and b-b and cross the current sheet at distances $v_{FE}\tau$ from the neutral lines. This point marks the boundary across which the field changes from the old steady state value to the new. The particles also achieve a new equilibrium state within $v_{FT}\tau$ of the neutral line, and are unchanged from the old configuration beyond $v_{OT}\tau$ (plasma sheet) and $3V_A\tau$ (energetic particles of speed $3V_A$). Between these points the layers vary linearly with distance from the old to the new equilibrium states, and are expanding outwards at the same speed as the separatrix beyond $v_{FT}\tau$. (iii) Configuration at a time τ after a 3-fold decrease in reconnection rate, i.e. returning from the equilibrium set up in (ii) to that shown in (i). Similar considerations to (ii) apply, but result in layer thinning.

based upon a single one-dimensional current sheet is both analytically tractable and gives good insight in a simple manner into the main effects resulting from time-dependent reconnection rates and neutral line motions. The limitations of the theory should be borne in mind, however, when comparing in detail our results with observations.

In the next section we will now go on to investigate how the one-dimensional solutions can be generalised to include time-dependent reconnection rates, though, as here, the neutral line will be assumed to be stationary in the Earth's frame.

(3) Effects of Time-Dependent Reconnection at a Stationary Neutral Line.

We now consider the effect on the configuration of the reconnected field region and accelerated particle populations which will result from variations of the reconnection rate. As indicated in the previous section the reconnection rate is just the electric field E_y at the neutral line, which we will now assume to be a function of time, $E_{yN}(t)$. Unlike the steady-state case where E_y is constant and uniform along the current sheet, we now have a system in which E_y varies in time and space, and is associated with variations in the magnetic field structure. As we will go on to show, the information about variations in E_y at the neutral line propagates away from it along the current sheet with the reconnected field lines, at approximately the Alfvén speed. Before turning to the calculation however, it should be reemphasised that we do not enquire why such changes in E_{yN} occur but only what their effects will be. As in the previous section we again assume uniform and constant inflow conditions (i.e. a lobe plasma with uniform density n and down-tail bulk flow speed v_i) and a sufficiently small reconnection rate that B_z is everywhere small compared to the total field strength outside the current sheet.

The solution of the problem is readily obtained by noting that the contraction speed v_F of the reconnected flux tubes determined by the equilibrium conditions (equations (2.6a) and (2.7a)) is independent of the reconnection rate. Thus as the reconnection rate varies, the B_z field threading the current sheet varies in concert, such that v_F remains constant. The B_z value at the current sheet of a given field line then remains fixed as it contracts away from the neutral line. Thus since the field line passing through the current sheet at position X at time t was reconnected at time

$$t' = t - |X - X_N|/v_F$$

we have

$$E_y(X,t) = E_{yN}(t - |X - X_N|/v_F)$$

and

$$B_z(X,t) = \frac{E_y(X,t)}{v_F} = \frac{E_{yN}(t - |X - X_N|/v_F)}{v_F} \quad (2.13)$$

where X_N is the neutral line position. Note that the curl of the electric field ($\delta E_y/\delta x$) is just such as to account for the time rate of change of the magnetic field B_z at a given position. It should also be noted that variations in the reconnection rate and the consequent variations in conditions along the current sheet will violate exact one-dimensionality. However, provided the variations are sufficiently slow that the spatial scale for variations along the current sheet is much greater than the current sheet thickness (as will generally be the case in practice), the one-dimensional stress balance condition will form a very good approximation at each point along the current sheet, as assumed in the analysis above. The same argument was previously employed by Cowley and Southwood (1980) in their treatment of the effect of spatially varying inflow plasma conditions as briefly discussed in the introduction to this thesis.

Equation (2.13) shows that at any particular time the value of B_z along the current sheet varies according to the past history of the reconnection rate at the neutral line. Consequently the separatrices and particle boundaries no longer lie in planes mapping back to the neutral line, as in the steady state case. Considering the magnetic separatrix first, we can use the flux conservations argument introduced in the last section to calculate the half thickness W of the region of reconnected field at any point X at time t . However, we must now integrate B_z between the point X and the neutral line (at position X_N), or equivalently integrate the value of $E_{yN}(t)$ over the field line time-of-flight from the neutral line to the point X . We thus have

$$W(X,t) = \frac{1}{B} \int_{X_N}^X |B_z(x,t)| dx \quad (2.14)$$

$$= \frac{1}{B} \int_{t-(|X-X_N|)/v_F}^t E_{yN}(t') dt' \quad (2.14)$$

Similarly, the distance D between the boundary of particles of speed v_p and the magnetic separatrix at position X and time t is obtained by noting that the flux contained in this region is that reconnected in the particle time of flight. So

$$D(X,t,v_p) = \frac{1}{B} \int_{t-(|X-X_N|)/v_p}^t E_{yN}(t') dt' \quad (2.15)$$

Thus the half thickness of the particle layer is given by

$$\begin{aligned} S(X,t,v_p) &= W(X,t) - D(X,t,v_p) \\ &= \frac{1}{B} \int_{t-(|X-X_N|)/v_F}^{t-(|X-X_N|)/v_p} E_{yN}(t') dt' \end{aligned} \quad (2.16)$$

When $E_{yN}(t') = E_y$, a constant, these equations reduce to the steady state case expressed in equations (2.9), (2.10) and (2.11). However, when E_{yN} varies in time, the magnetic separatrix and the particle boundaries will in general be in motion with speeds (Z-direction) given by

$$V_W = \frac{\delta W}{\delta t} = \frac{[E_{yN}(t) - E_{yN}(t - |X - X_N|/v_F)]}{B} \quad (2.17a)$$

and

$$V_S = \frac{\delta S}{\delta t} = \frac{[E_{yN}(t - |X - X_N|/v_p) - (E_{yN}(t - |X - X_N|/v_F))]}{B} \quad (2.17b)$$

Using equations (2.14) and (2.16) the structure of the reconnected field region and associated accelerated particle populations may be calculated for arbitrary

variations of the reconnection rate. Here we will illustrate the effects which occur for two simple changes, a sharp increase and a sharp decrease in the reconnection rate. Technically, such rapid changes in the reconnection rate leading to rapid variations in conditions along the current sheet will violate the one-dimensional current sheet approximation. However, the effects which such changes produce may readily be comprehended, leading to insight into the behaviour for more general and more gradual variations. Appropriate diagrams are shown in Figure (2.2) in the format previously described. The upper diagram (Figure (2.2i)) is the steady state picture for $v_i = 0.3 V_A$ and $E_y = V_{AB}/4$ previously described, the dot-dash line being the boundary of particles of speed $v_p = 3 V_A$. We now consider the result of a three-fold increase in the reconnection rate, noting that when the new equilibrium is established the layer widths will all have increased by this factor compared with Figure (2.2i). Figure (2.2ii) shows the approach to this new equilibrium after an arbitrary time τ . If we first consider the magnetic field, then B_z (and E_y) has tripled its initial value to distances $v_F \tau$ on either side of the neutral line (as marked in the figure), it (and E_y) then discontinuously changes to the original equilibrium value at larger distances. The last field lines reconnected before the change are marked as a-a and b-b and pass through the current sheet at distances $v_F \tau$ on either side of the neutral line respectively. Within $v_F \tau$ the field has reached its new equilibrium configuration, while further away it has yet to respond, although, of course, the magnetic separatrix is moving away from the current sheet at speeds V_{WE} and V_{WT} on the Earthward and tailward sides of the neutral line respectively in these regions. It should be noted that this separatrix speed corresponds only to the motion of a topological boundary (marked by the trajectories of particles of "infinite" speed), and that the motion of the inflow plasma is in no way affected. Turning now to the boundary of particles of arbitrary speed v_p , we note that the new equilibrium locations will have been attained within distances $v_F \tau$ of the neutral line, while the boundaries will be totally unaffected at distances greater than $v_p \tau$ (as shown). Between these two distances the boundary position varies linearly between the new and old equilibrium locations, and expands uniformly outwards at the same speed as the separatrix, thus maintaining a constant distance from it.

Figure (2.2iii) shows an analogous situation produced by a sudden decrease in the reconnection rate. We suppose that equilibrium has been achieved in the region shown due to the three-fold increase described above, and we suppose

that there is then a sudden decrease in E_y back to the original value. The figure again shows the system a time τ after the change, exactly similar considerations applying as discussed above.

(4). Effects of Neutral Line Motion

The second effect which will lead to time-dependent variations in the accelerated particle populations downstream from the neutral line, is motion of the neutral line itself. In this section we will discuss these effects and set up a general theory which allows arbitrary simultaneous variations in both the reconnection rate and the speed of the neutral line. Again, we do not enquire about the cause of these variations, but simply investigate their consequences. We also retain the small B_z approximation employed above, which, as we will see, not only requires a sufficiently small reconnection rate for its validity, but also a neutral line speed which is not too large. We also assume, as previously, that the variations in reconnection rate and neutral line motions which occur are not so rapid that the one-dimensional current sheet approximation is violated.

Let us first assume for simplicity that the reconnection rate E_{yN} is constant in time and that the neutral line is moving at a steady speed

$$v_N = \frac{dX_N}{dt}$$

(such that v_N is positive if the neutral line is moving in the $+x$ direction). Again we emphasise that the contraction speed of the field lines along the current sheet v_F is independent of the neutral line motion. Then if we consider the flux reconnected in unit time (E_{yN} webers per unit length of neutral line) then on the Earthward side of the neutral line (in the direction of motion of the neutral line) this will be contained in a length of the current sheet given by $(v_{FE} - v_N)$, while on the tailward side of the neutral line it will be contained in length $(v_{FT} + v_N)$. Thus by flux conservation we have

$$B_z E = \frac{E_{yN}}{(v_{FE} - v_N)} \quad (2.18a)$$

and

$$B_{zT} = \frac{E_{yN}}{(v_{FT} + v_N)} \quad (2.18b)$$

Thus the field threading the current sheet is "compressed" by neutral line motion "ahead" of the neutral line and "rarefied" behind it. It should be noted that B_z diverges as v_N approaches either v_{FE} or $-v_{FT}$; the speed of the neutral line is clearly constrained to lie between the limits imposed by the contraction speeds of the reconnected field lines along the current sheet on either side. The small B_z approximation imposes a somewhat more stringent limit on v_N , however, in that v_N must not approach either v_{FE} or $-v_{FT}$ so closely that B_z becomes comparable with B . It should also be noted that the electric fields E_y will be different on either side of the neutral line and given by

$$E_{yE} = v_{FE} B_{zE} = \frac{v_{FE}}{(v_{FE} - v_N)} E_{yN} \quad (2.19a)$$

and

$$E_{yT} = v_{FT} B_{zT} = \frac{v_{FT}}{(v_{FT} + v_N)} E_{yN} \quad (2.19b)$$

on the Earthward and tailward sides of the neutral line respectively. Thus the electric field "ahead" of the neutral line is larger than E_{yN} while that "behind" the neutral line is smaller than E_{yN} .

The curl in the electric field ($\delta E_y / \delta x$) across the neutral line region is just such as to account for the temporal change in B_z which occurs as the neutral line passes across a given location. Equations (2.18) and (2.19) may also be derived using the steady-state theory of section (2) by applying a frame transformation to the (instantaneous) rest frame of the neutral line. In the transformed frame the electric fields are then, of course, the same on either side of the neutral line (and equal to E_{yN}), while the difference between B_{zE} and B_{zT} is interpreted in terms of the field-aligned speed of the inflow plasma in this frame equal to $v_i + v_N$.

We now consider the general case of arbitrary variation in the reconnection rate and neutral line motion (the latter is limited to be less than the field line speeds v_F in either direction). If we consider the value of B_z threading the current sheet at any position X and at time t , then this is determined by equations (2.18),

where E_{yN} and v_N are evaluated at the time t_R that the corresponding field line was reconnected. As before, the B_z field threading the current sheet for a given flux tube is fixed once it has reconnected, due to the constant and uniform contraction speed v_F along the current sheet (for the constant and uniform inflow plasma conditions assumed here). We thus require to calculate $t_R = t_R(v_F, X, t)$. For the field line which threads the sheet at (X, t) , its position X' at any other time t' is given by

$$X'(t') = X + v_F (t' - t).$$

Let us then suppose that the position of the neutral line as a given function of time is $X_N(t)$. Then t_R is determined by the equations (for the regions either side of the neutral line)

$$X_N(t_R) = X + v_{FE} (t_R - t) \quad (2.20a)$$

$$X_N(t_R) = X - v_{FT} (t_R - t) \quad (2.20b)$$

For simple variations of X_N corresponding e.g. to piecewise constant speeds or acceleration equation (2.20) is easy to solve analytically but in general must be solved either numerically or graphically. The graphical representation is shown in Figure (2.3). In this figure the vertical scale is the position X , and the horizontal scale is time t . The curved line AA shows the path of the neutral line, while the dashed lines show the paths of the current sheet intersection point of the reconnected field lines. Field lines reconnected at any time start from the neutral line AA and move on straight line paths whose angle to the horizontal axis is $\tan^{-1} v_{FE}$ earthward of the neutral line and $\tan^{-1} v_{FT}$ tailward of it. If we consider the field line which passes through the current sheet at position X at time t (point P in Figure 2.3) then the time t_R of reconnection of that field line, and the position of the neutral line X_R at this time, are determined by projecting back along the dashed line through P until the neutral line trajectory is intersected, as shown. If the neutral line trajectory is constrained to be less than the field line speeds in either direction then clearly there will be only one intersection, i.e. only one real solution of equation (2.20).

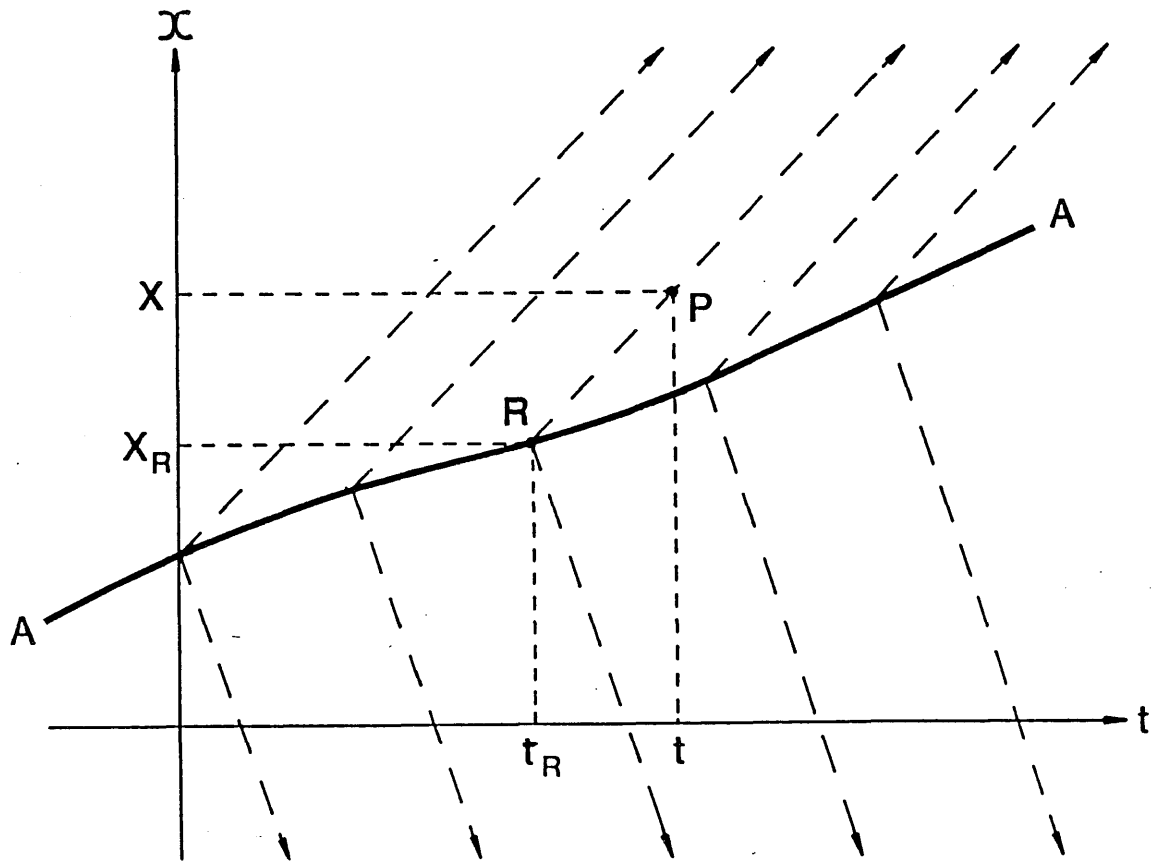


Figure 2.3. Diagram illustrating the graphical solution to equation (2.20), determining the time t_R at which a given field line located at X at time t was reconnected. Position along the current sheet is plotted vertically and time horizontally, and the trajectory of the neutral line is the solid line A-A. The dashed lines show the trajectories of the reconnected field lines (their centre plane intersection points) contracting away from the neutral line on either side. To find t_R for a given X, t (point P) the field line trajectory is traced back to its neutral line trajectory intersection point, R, as shown.

Turning now to the widths of the flux and particle layers, the arguments introduced earlier can be used to show immediately that at (X,t) the half-width of the reconnected field layer is

$$W(X,t) = \frac{1}{B} \int_{t_R(v_F, X, t)}^t E_{yN}(t') dt' \quad (2.21)$$

while that of particles of speed v_p is given by

$$S(X,t,v_p) = \frac{1}{B} \int_{t_R(v_F, X, t)}^{t_R(v_p, X, t)} E_{yN}(t') dt' \quad (2.22)$$

where $t_R(v_p, X, t)$ is the time that the bounding field line corresponding to v_p was reconnected, given by (in direct analogy with equations (2.20))

$$X_N(t_R) = X + v_p(t_R - t) \quad (2.23)$$

where v_p has to be reversed in sign tailward of the neutral line. This equation can again be solved either analytically for simple $X_N(t)$, or numerically or graphically using a diagram analogous to Figure (2.3).

Using equations (2.20) and (2.23) we find that

$$\frac{dt_R(v_{FE}, X, t)}{dt} = \frac{v_{FE}}{[v_{FE} - v_N(t_R)]} \quad (2.24a)$$

$$\frac{dt_R(v_{FT}, X, t)}{dt} = \frac{v_{FT}}{[v_{FT} + v_N(t_R)]} \quad (2.24b)$$

$$\frac{dt_R(v_p, X, t)}{dt} = \frac{v_p}{[v_p \pm v_N(t_R)]} \quad (2.24c)$$

where the lower/upper signs in equation (2.24c) correspond to the regions tailward/Earthward of the neutral line respectively. Thus the separatrix speed (z -direction) is given by

$$V_{WE} = \frac{1}{B} \left(E_{yN}(t) - \frac{v_{FE}}{(v_{FE} - v_N[tR(v_{FE})])} \cdot E_{yN}[tR(v_{FE})] \right) \quad (2.25a)$$

and

$$V_{WT} = \frac{1}{B} \left(E_{yN}(t) - \frac{v_{FT}}{(v_{FT} - v_N[tR(v_{FT})])} \cdot E_{yN}[tR(v_{FT})] \right) \quad (2.25b)$$

for regions earthward and tailward of the neutral line, respectively, while the particle layer speed is given by

$$V_{SE} = \frac{1}{B} \left(\frac{v_p}{(v_p - v_N[tR(v_p)])} E_{yN}[tR(v_p)] - \frac{v_{FE}}{(v_{FE} - v_N[tR(v_{FE})])} \cdot E_{yN}[tR(v_{FE})] \right) \quad (2.26a)$$

and

$$V_{ST} = \frac{1}{B} \left(\frac{v_p}{(v_p + v_N[tR(v_p)])} E_{yN}[tR(v_p)] - \frac{v_{FT}}{(v_{FT} + v_N[tR(v_{FT})])} \cdot E_{yN}[tR(v_{FT})] \right) \quad (2.26b)$$

When v_N is zero, equations (2.25) and (2.26) clearly reduce to equations (2.17a,b) deduced for variable reconnection rate while for constant reconnection rate E_{yN} and steady neutral line motion we find

$$V_{WE} = - \frac{v_N}{(v_{FE} - v_N)} \cdot \frac{E_{yN}}{B} ; \quad V_{WT} = \frac{v_N}{(v_{FT} + v_N)} \cdot \frac{E_{yN}}{B}$$

and

$$V_{SE} = - \frac{v_N(v_p - v_{FE})}{(v_p - v_N)(v_{FE} - v_N)} \cdot \frac{E_{yN}}{B} ;$$

$$V_{ST} = \frac{v_N(v_p - v_{FT})}{(v_p + v_N)(v_{FT} + v_N)} \cdot \frac{E_{yN}}{B} \quad (2.27a-d)$$

The latter equations may also be derived from the steady state formulae (2.9) and (2.11) on applying a transformation into a frame in which the neutral line moves with speed v_N .

In Figure (2.4) we illustrate the effects of neutral line motion on the accelerated particle layers by showing three paradigm cases, corresponding to steady motion (Figure 2.4(i)), a sudden onset of motion (Figure 2.4(ii)) and a sudden cessation of motion (Figure 2.4(iii)). The reconnection rate is taken to be constant, and the inflow conditions assumed are identical to those taken previously (as in Figure 2.2). However, now the neutral line is taken to move downtail (from left to right in the figure) with speed $0.7 V_A$. Since this speed exceeds the assumed down-tail flow speed of the tail lobe plasma ($0.3 V_A$) the asymmetry about the neutral line is reversed in sense compared with that occurring with no neutral line motion (Figure 2.2(i)). Due to this motion, $|B_z|$ is now larger tailward of the neutral line than Earthward of it.

In Figure 2.4(ii) we show the system at an arbitrary time τ after the neutral line starts to move at the above speed, having initially been stationary. The diagram therefore shows the system in transition between the steady configurations (relative to the neutral line) shown in Figures 2.2(i) and 2.4(i). The initial position of the neutral line $X_N(0)$ is shown by the vertical arrow, and the last field lines reconnected before the neutral line starts to move are marked a-a, and b-b, these passing through the current sheet at distances $v_F\tau$ from $X_N(0)$ as shown. Within these distances the field configuration (relative to the neutral line) is identical to that in Figure 2.4(i), while at larger distances the field has yet to respond, and therefore has the configuration of Figure 2.2(i). Note particularly that in this case the separatrix does not move in this outer region, since the reconnection rate is steady. Similarly the layers of particles of speeds v_0 (plasma sheet particles) and $3 V_A$ (high energy particles bounded by dot-dashed line) have reached their final configuration (relative to the neutral line) within $v_F\tau$ of $X_N(0)$, but are unchanged beyond distances of $v_0\tau$ and $3V_A\tau$ respectively. Their variations are then linear between these positions.

Finally, in Figure 2.4(iii) we show the configuration which occurs at time τ after the neutral line has ceased moving, thus showing the transition from the configuration of Figure 2.4(i) back to Figure 2.2(i). Similar considerations apply in this case as to Figure 2.4(ii).

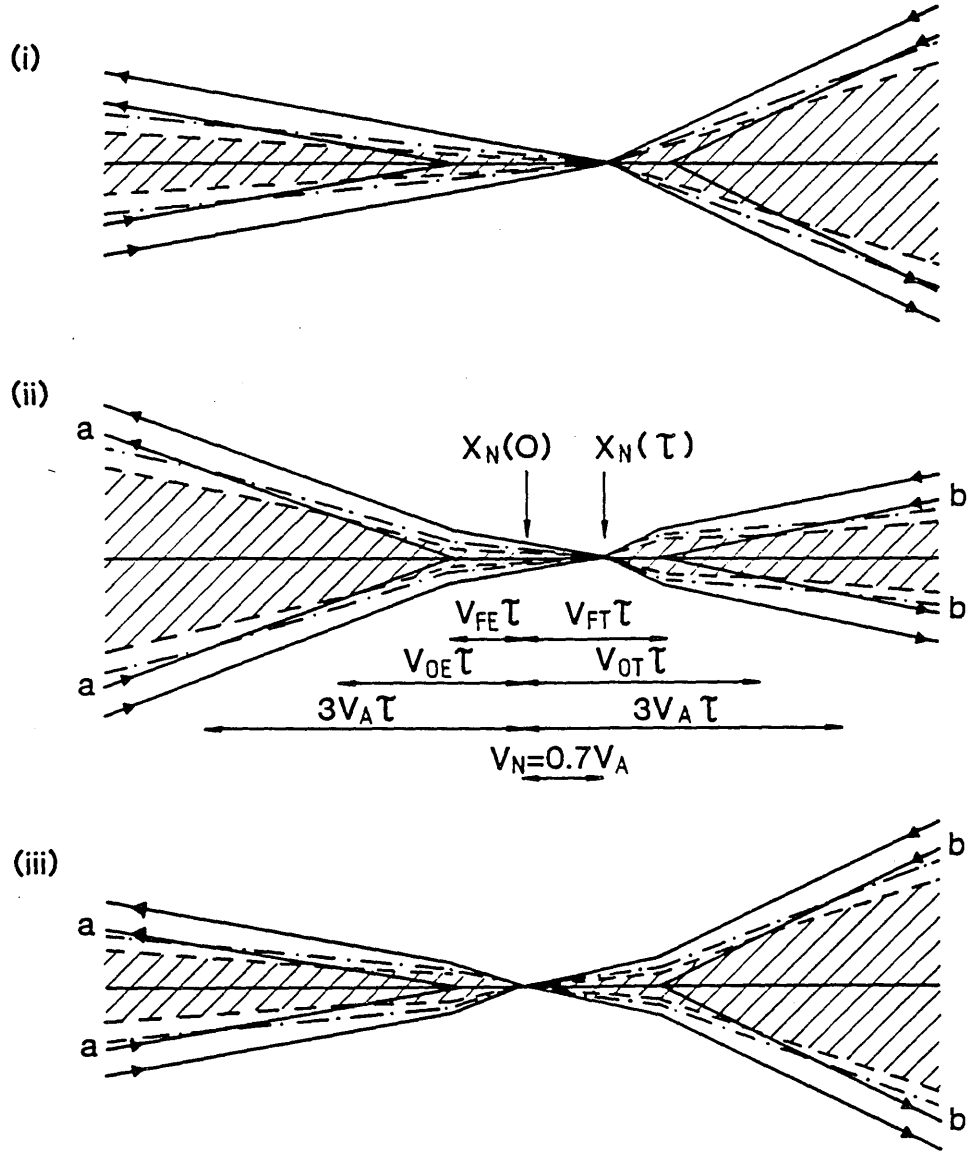


Figure 2.4. Effects of neutral line motion on the field and particle layer structure for a constant reconnection rate, using the same conditions and format as Figure 2.2. Figure (i) shows the effect of steady neutral line motion at speed $0.7 V_A$ from left to right. The asymmetry about the neutral line is reversed compared with Figure 2.2(i) as this speed exceeds the lobe flow speed, resulting in a larger B_z "ahead" (to the right) of the neutral line than "behind" it. Figure (ii) shows the configuration at a time τ after the neutral line suddenly starts to move at the above speed, having previously been at rest, representing the transition from Figure 2.2(i) to 2.4(i). $X_N(0)$ is the initial position of the neutral line, and last field lines reconnected before the change (a-a, b-b) cross the current sheet at distances v_{FT} from this point. Within these distances from $X_N(0)$ the field and particle layers have achieved a configuration (relative to the neutral line) identical to that in (i). These particles are unaffected beyond v_{OT} (plasma sheet) and $3 V_A\tau$ (energetic particles of speed $3 V_A$) from $X_N(0)$, and vary linearly between these positions. (iii) Configuration at time τ after cessation of the neutral line motion, representing the transition from Figure 2.4(i) back to Figure 2.2(i). Similar arguments to (ii) apply.

(5). Phenomenological Substorm Model

The theory developed in the previous sections can now be used to produce a phenomenological model of plasma sheet and energetic particle layer behaviour during substorms in the earth's geomagnetic tail, using variations in the reconnection rate and motions of the neutral line inferred from observations (see Hones 1984, 1985 and references therein). We will also use typical magnetotail parameters taken from the ISEE 3 geotail mission data sets (see e.g. Slavin et al., 1985). The aim here is not to give a complete description of the behaviour in the tail during substorms but to illustrate the utility of the theory in giving insight into the effects resulting from time dependence. The results should have a semi-quantitative applicability to expected conditions in the tail, but do not give a complete quantitative picture due to the limitations of the theory outlined in the penultimate paragraph of section (2) of this chapter. Since the behaviour of the distant tail has been a subject of particular interest in recent years, we will discuss the implications of the theory for this region in detail, specifically at 200 R_E , showing how it can be used to obtain a basic understanding of the observations. This will be illustrated further in the next chapter, where a case study of a particular substorm event is considered.

In the neutral line model of the substorm (Hones, 1984, 1985), the quiet time configuration is formed by slow reconnection at a neutral line deep in the tail, which is then disturbed by the formation of a new neutral line within the plasma sheet much closer to the earth, at which the reconnection rate is more rapid. Reconnection at the new neutral line results initially in the formation of closed loops of magnetic flux containing trapped plasma within the earthward plasma sheet, but after the reconnection has proceeded sufficiently far such as to disconnect the entire plasma sheet from the earth, then the latter is ejected down the tail by magnetic tension forces, together with the old neutral line, as a closed loop plasmoid structure. Rapid reconnection continues at the new near-earth neutral line for some time, but later recovery begins and the quiet time configuration is regained with the movement of the new neutral line back into the deep tail and reductions in the reconnection rate.

Having briefly recapped the substorm model we will now consider the specific values used in our calculations. In line with the above discussion we start by assuming that during the pre-substorm quiet time the neutral line lies at large distances downtail and that the reconnection rate is small. ISEE-3 results

suggest that the quiet time neutral line lies between 60 and 120 earth radii downtail (Daly et al. (1984); Baker et al. (1984b); Cowley et al. (1984); Zwickl et al. (1984)) and here we take a distance of 100 R_E . We also assume that a typical quiet-time potential of 30 kV exists across a 50 R_E wide tail, giving a value of $E_y = 0.1 \text{ mV m}^{-1}$. Assuming a typical lobe magnetic field strength $B = 10 \text{ nT}$ and a plasma density $n = 0.1 \text{ cm}^{-3}$ (Slavin et al. (1985)) we have an Alfvén speed just outside the current sheet $V_A \approx 500 \text{ km s}^{-1}$. Zwickl et al. (1984) report that the downtail lobe plasma bulk speed distribution is centred around 150 km s^{-1} , and so we will use this value for the downtail lobe flow speed v_i . Equations (2.6a) and (2.7a) in section (2) then give field line contraction speeds $v_{FE} = 350 \text{ km s}^{-1}$ earthward and $v_{FT} = 650 \text{ km s}^{-1}$ tailward of the neutral line, while equations (2.6b) and (2.7b) give plasma sheet particle speeds of $v_{OE} = 850 \text{ km s}^{-1}$ (3.8 keV for protons) and $v_{OT} = 1150 \text{ km s}^{-1}$ (6.9 keV protons) earthward and tailward respectively (compatible with average observed values of 890 km s^{-1} (Richardson and Cowley, 1986)).

Substorm onset is marked by the sudden formation of a second neutral line much closer to the earth, taken here to be located at 20 R_E . The cross tail voltage along this neutral line is believed to be of order 100 kV giving $E_y = 0.4 \text{ mV m}^{-1}$, if a substantial fraction of the width of the tail is involved. (It has also been suggested that reconnection may have an explosive onset, with as much as 1 MV across the tail (Coroniti 1985) but we have not included such voltages here). This new neutral line is initially located within a region not accurately described by our model, as it lies within that region of the near earth, isotropised plasma sheet occupied by mirroring particles. However, since the reconnection rate at the new neutral line is so much higher than at the old neutral line, the two become connected by the same field line ≈ 8 minutes after onset, with the newly formed plasmoid lying between them. After this time, once the plasmoid has been disconnected, the inflow to the near earth neutral line and downstream plasma sheet comes from the lobe plasma, and our theory is then valid. For simplicity we will assume that reconnection in the deep tail ceases at the point in time that the plasmoid is disconnected. This need not necessarily be the case but the effects of reconnection at the old neutral line will in any case not be important (unless the reconnection rate there is suddenly enhanced above its quiet time value, which seems unlikely). After the plasmoid becomes disconnected from the Earth the flux reconnected at the new neutral line is wrapped over and around the plasmoid, and the field tension

accelerates it down the tail. Here we will assume for simplicity that there is no "slippage" of flux around the sides of the plasmoid, such that it moves downtail at the tailward reconnected field line speed $v_{FT} = 650 \text{ km s}^{-1}$. This is consistent with observed plasmoid speeds of between 300 km s^{-1} and 1000 km s^{-1} (Hones 1984, Richardson et al., 1986; Richardson and Cowley (1986)). We would expect the plasmoid length to reflect the initial separation of the two neutral lines, i.e. to be of order $80 R_E$ in length. Plasmoids at $200 R_E$ are believed to have a full thickness of $\approx 20 R_E$ (Hones 1984; Hones et al., 1984; Baker et al., 1984a), and we will therefore assume these values in our model. We have also assumed the plasmoid boundary is formed by 2 arcs of a circle giving the above dimensions. Some time after the plasmoid has left the near earth tail the recovery phase begins, associated with downtail motion of the neutral line and a decline in the reconnection rate. Recovery lasts for about one hour, and ends with the neutral line having returned to the deep tail position at $100 R_E$. This implies an average neutral line speed of 140 km s^{-1} . We will assume sudden onset of tailward motion of the new neutral line at this speed some 35 mins after the plasmoid has been released, and a sudden stop when the neutral line reaches $100 R_E$ one hour later. During this period the reconnection rate also falls to the quiet time value. We shall assume a linear decrease during this period, equivalent to a decrease in reconnection rate of $0.3 \text{ mV m}^{-1} \text{ hr}^{-1}$.

These assumed variations are shown graphically in the upper part of Figure 2.5. The top panel shows the assumed reconnection rates, plotted against time after onset of reconnection at $20 R_E$, at the new (full line) and old (dashed line) neutral lines respectively, while the middle and lower panels show the speed and position of the new neutral line. In the centre panel we illustrate the results by showing the variations of the separatrices (solid lines), plasma sheet (hatched region) and energetic particle layers (dotted and dot-dashed lines) versus time, $200 R_E$ down-tail from the Earth. The vertical scale is perpendicular distance from the tail centre panel, while the squared region corresponds to the down-tail propagating plasmoid. The lower panel shows the corresponding variation of B_z at the current sheet with the field within the plasmoid being shown dashed, since it is not predicted by our model but simply sketched in on the basis of observation.

The onset of reconnection at $20 R_E$ within the pre-substorm plasma sheet is marked at $t = 0$ in Figure 2.5. Before this time the steady state theory described

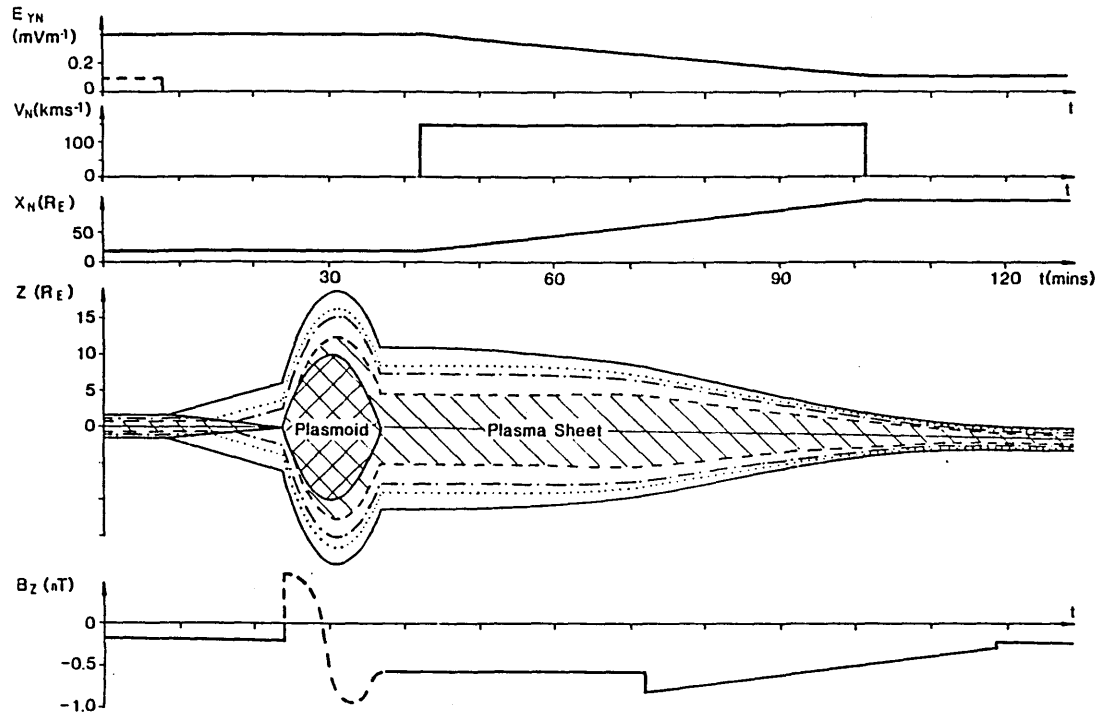


Figure 2.5. This figure shows the results of applying the time-dependent reconnection theory to substorms in the geomagnetic tail, specifically showing how the plasma sheet and energetic particle layers vary in the distant tail ($200 R_E$ from Earth) during a substorm. The top panel shows the assumed variations of the reconnection rate at the old (dashed line) and new (solid line) neutral lines, against time after onset of reconnection at $20 R_E$ ($t=0$). The reconnection rate at the old neutral line is initially 0.1 mV m^{-1} falling to zero at $t = 8$ mins, when the plasmoid becomes disconnected. At the new neutral line the rate is constant at 0.4 mV m^{-1} between 0 and 43 minutes and then drops linearly to 0.1 mV m^{-1} during the recovery phase (ending at $t = 103$ mins). The next two panels show the speed $v_N(t)$ and position $X_N(t)$ of the new neutral line respectively. The neutral line moves from 20 to $100 R_E$ at 140 km s^{-1} during recovery. The pre-substorm neutral line is assumed initially to lie at a distance of $100 R_E$, and then to move tailward at the speed of the plasmoid (the same speed as the reconnected field lines tailward of the new neutral line, i.e. 650 km s^{-1}) after plasmoid disconnection. The fourth panel shows the variations in thickness of the reconnected field layer and plasma populations at $200 R_E$ downtail during the substorm period, based on these assumed variations. The horizontal solid line is the central current sheet, while other solid lines represent the field separatrices, the hatched region the plasma sheet and the dot-dashed and dotted lines the energetic particle boundaries for particles of 2000 km s^{-1} and 3000 km s^{-1} respectively. The squared region corresponds to the downtail propagating plasmoid. The lower panel shows the variation of B_z through the current sheet during the substorm, the curve during the plasmoid passage across $200 R_E$ being dashed in on the basis of observation, since this is not determined by our theory.

in section 2, applied to a neutral line at 100 R_E with $E_y = 0.1 \text{ mV m}^{-1}$ and the parameters given above is sufficient to describe the structure at 200 R_E . This gives a z-component of the magnetic field of -0.15 nT and a plasma sheet (composed of tailward jetting ions of speed 1150 km s^{-1}) of full thickness 1.3 R_E . An observer earthward of the neutral line would see a larger B_z of 0.29 nT , and relatively thicker plasma sheet (full thickness of 1.3 R_E at only 40 R_E earthward of the neutral line i.e. 60 R_E downtail) during the initial quiet time phase.

After rapid reconnection begins in the near earth tail, there is a short period at 200 R_E before any changes begin. This is the time required for the new neutral line to reconnect the flux within the quiet time plasma sheet ending in disconnection of the plasmoid. At a reconnection rate of 0.4 mV m^{-1} this takes about 8 minutes, and until this time the configuration at 200 R_E is determined purely by the deep tail neutral line. At $t=8$ minutes the plasmoid is disconnected and starts to move down the tail, and we assume that the old neutral line, along which the reconnection rate has dropped to zero, moves with it. The configuration at 200 R_E is then determined by two components: firstly, closest to the centre plane the structure is due to the down-tail motion of the old neutral line. The field and particle layers thin, reaching zero thickness when the old neutral line and plasmoid arrive at $t = 24.4$ mins after onset. The value of B_z is constant at -0.15 nT up to this point. However, the structure is surrounded by an expanding layer of flux reconnected at the new neutral line during this period, and associated energetic particles, which have travelled along the field lines draped around the plasmoid structure. These particles begin to arrive at $t \approx 14$ mins and $t \approx 18$ mins for 3000 km s^{-1} and 2000 km s^{-1} particles respectively. Plasma sheet particles resulting from reconnection at the new neutral line do not appear at 200 R_E until after the arrival of the plasmoid. The expansion speed of the layers prior to plasmoid arrival is 30 km s^{-1} . This value includes both the effects of contraction of the old particle layers and expansion due to reconnection at the new neutral line.

At $t = 24.4$ minutes the leading edge of the plasmoid arrives at 200 R_E , and very shortly afterwards the first plasma sheet particles from the new neutral line arrive, at $t \approx 25$ mins. As the plasmoid moves past, the field and particle layers are displaced outwards, but also continue to expand as more flux is reconnected. During the passage of the plasmoid the B_z component of the magnetic field suggested by observation, shows a bipolar variation about zero,

of amplitude a few nanoteslas. At $t = 37.5$ minutes after onset the trailing edge of the plasmoid passes 200 R_E , along with the first lobe field line reconnected at the new substorm neutral line. After this time a steady-state "post-plasmoid" plasma sheet and field wedge are present due to steady reconnection at 20 R_E , and remains until tailward neutral line retreat and reconnection rate reduction begins at $t = 43$ mins. At this point the plasma sheet has a full thickness of 9.6 R_E (although this will be an underestimate as we have neglected any inflation due to the perpendicular pressure of the plasma), and a z-component of the magnetic field $B_z = -0.6$ nT.

At 43 minutes after the onset of reconnection at 20 R_E and shortly after the departure of the plasmoid from 200 R_E , the recovery phase begins. For the first ≈ 30 minutes there is only slight thinning of the field and higher energy particle layers and hardly any change in the lower energy particle layers, due to the opposing effects of the approaching neutral line and reconnection rate reduction. However, after the first field line reconnected after the onset of neutral line motion passes 200 R_E (when B_z jumps from -0.6 nT to -0.8 nT) at $t = 72.6$ mins, the magnetic flux passing 200 R_E is much greater than that being reconnected at the neutral line, and consequently the particle and field layers begin to thin rapidly.

At $t = 103$ minutes the neutral line reaches 100 R_E , the reconnection rate has dropped to 0.1 mV m^{-1} , and the B_z component of subsequently reconnected field lines settles at -0.15 nT again. These field lines reach 200 R_E 16.4 minutes later ($t = 119.4$ mins), by which time the field and particle layers have thinned to their quiet time thickness, and the initial steady state is resumed, completing the substorm cycle.

Using the results obtained above we can then understand the gross features observed by spacecraft at 200 R_E during a substorm and passage of a plasmoid. This is heavily dependent on the distance above the centre plane of the tail. Only spacecraft within ≈ 2 R_E of the centre plane will observe any quiet time plasma sheet phenomena, whilst substorm effects may be observed to distances of at least 18 R_E . Consequently there are expected to be relatively few observed encounters with the quiet time plasma sheet, most hot plasma observations resulting from encounters with the substorm plasmoid and post plasmoid plasma sheet, in agreement with the observations of Baker et al. (1984a). Encounters with the plasmoid itself will only occur for spacecraft

within $\approx 10 R_E$ of the centre plane, first passing through the energetic particle layers, the highest energy particles being observed earliest, then into the plasmoid, where the total field strength will drop, and the plasma density rises. On emerging from the plasmoid the spacecraft may spend an extended length of time in the post-plasmoid plasma sheet or associated energetic particle layer, before the particle structures collapse at the end of the substorm and the spacecraft moves back into the lobe plasma. A spacecraft between 10 and 18 R_E from the current sheet will just spend a brief period in the energetic particle layers as the plasmoid passes by closer to the centre plane, whilst at 19 R_E and beyond, only field perturbation will be observed, corresponding to the travelling compression regions described by Slavin et al. (1984).

Of course, this description represents only a simplified picture of possible observations, and does not account for effects due, for example, to large scale motions of the tail structure. However we believe that the model gives a useful picture on which the basic behaviour of the distant tail (and other tail phenomena) may be understood.

(6). Summary

In this chapter we have shown how the simple steady state models of reconnection based on local 1-D stress balance conditions described by Cowley (1980) and Cowley and Southwood (1980) can be generalised to include the time dependent effects of varying reconnection rate and neutral line motion. Provided the reconnection rate and the speed of the neutral line do not vary too rapidly in time the one-dimensional current sheet approximation should remain valid downstream from the neutral line, such that the corresponding stress balance condition can be locally applied at each point of the current sheet. This condition then determines the contraction speed of the reconnected field lines away from the neutral line, which depends only on the conditions in the lobes on either side of the current sheet, and is independent of neutral line conditions. This property allows straightforward calculation of field and particle layer thickness by use of the principle of flux conservation in the reconnected field wedge. This technique is readily generalised to include arbitrary variations in reconnection rate and neutral line velocity, providing the z-component of the magnetic field remains small compared with the lobe field.

We have shown that increases in the reconnection rate result in an increase in B_z and a thickening of the layers on both sides of the neutral line; for a sudden step increase the last field line reconnected before the change marks the boundary of the new steady state at its intersection with the current sheet. Further away from the neutral line the field and particle layers expand linearly at speeds which depend on the difference in the two reconnection rates, although this expansion region is of limited extent for the particle layers, depending on how far downstream the particles originating from the vicinity of the neutral line in that layer have travelled. Conversely, decreasing the reconnection rate results in a general thinning of the layers.

Neutral line motion results in a compression of the field ahead of the neutral line leading to an increased B_z and thicker field and particle layers, whilst behind the neutral line the field is rarefied, B_z falls and the layers thin. The thickness of the layers depends on the neutral line speed, and hence changes in the latter again affect the field and particle structure. Step changes in neutral line speed result in similar regions of transition and steady state described for varying reconnection rate, although on one side of the neutral line the layers thin, whilst on the other they thicken.

Finally, by way of an example, we have applied the theory to the case of the geomagnetic tail using parameters and neutral line behaviour inferred from observations to produce a phenomenological substorm model, in which we calculate the variations in plasma sheet and energetic ion boundary layer thickness at 200 R_E for the duration of a substorm. The calculations show that the quiet time plasma sheet is of order 1-2 R_E thick due to a relatively close neutral line where the reconnection rate is small, whilst during disturbed times, the neutral line is much further away (close to the Earth at $\approx 20 R_E$), and the reconnection rate is enhanced, resulting in a much thicker plasma sheet ($\approx 10 R_E$). We believe that the work presented here forms a useful basis on which the behaviour of the time-dependent tail may be understood, and in the next chapter we present a case study of a substorm event (taken from the CDAW-8 data analysis workshop) in which the applicability of this work (and other aspects of the neutral line model of substorms) will be discussed further.

CHAPTER 3.

ISEE-3 OBSERVATIONS IN THE DEEP GEOMAGNETIC TAIL

1. Introduction.

In the last chapter simple models of time dependent reconnection, including the effects of variable reconnection rates and motion of the neutral line itself, were presented. This led to a phenomenological description of substorms in the deep geomagnetic tail, using typical parameter values which have been deduced from a number of statistical studies of the ISEE-3 data sets (e.g. Zwickl et al., 1984; Scholer et al., 1984; Daly et al., 1984; Slavin et al., 1985). In this chapter, by way of testing the results and predictions of this theory against observation, we shall present a case study of a substorm event from the tail data set, using ISEE-3 energetic ion, thermal plasma electron, and magnetic field data, and several near Earth data sets which are used to relate the events observed in the tail to the prevailing geomagnetic conditions. The interval of data concerned, from the 28th January 1983 is one of the eight events studied as part of the eighth Coordinated Data Analysis Workshop (CDAW-8), which attempted a major evaluation of models of magnetospheric substorms. This program used a wide range of data, from spacecraft in the upstream solar wind, to ground based observations, and from geostationary and near-Earth spacecraft, to ISEE-3 in the deep tail. The intervals of data studied as part of this program also covered a wide range of geomagnetic activity levels, and so exhibit a variety of phenomena, which allow the various models of the substorm process to be critically evaluated, as well as revealing several new aspects of magnetospheric physics. Results from this major effort (e.g. Richardson et al., 1988, Baker et al., 1988) are shortly to be published in a special issue of the Journal of Geophysical Research, and so are not the major focus of interest here. Rather, we shall discuss in detail a single event from the CDAW-8 intervals (Interval A, 0400 - 1100 UT, 28th January 1983), with particular emphasis on the comparison of the theoretical aspects described in the last chapter with observations from the deep tail. It may be argued that the particular data interval chosen is the most "classic" of the CDAW intervals, and best fits the present purposes. However, this event does contain unique aspects (the lobe parameters are far from the typical values employed in the last section for example), and, in any case, the CDAW-8 intervals as a whole tended to support the neutral line model of substorms above other models (e.g. the viscous model proposed by Heikkila (1982,1987), and the boundary layer dynamics model of Rostoker and Eastman (1987)). As such it could be shown that most of the CDAW events agree, to a quantitative degree, with many of the theoretical aspects of the last chapter (see Richardson et al., 1988). Event A is therefore

chosen as a representative event, which has the benefit of being the least complicated of the intervals (containing a single isolated substorm), whilst displaying most of the aspects of substorms, as observed in the deep tail.

In the next section we shall briefly describe the instrumentation on board ISEE-3 from which the data in this study were taken, before discussing the event and its relationship to the theory described in the last chapter in detail in Section 3.

2. Instrumentation.

The ISEE-3 data presented in subsequent sections of this chapter are taken from three instruments on the spacecraft. These detect thermal plasma electrons, energetic ions, and the magnetic field within the spacecraft environment.

The thermal electron data were provided by the Los Alamos National Laboratory plasma analyser (Bame et al., 1978). This instrument makes its measurements of electrons in the energy range 8.5 eV to 1.1 keV in the plane perpendicular to the spacecraft spin axis, which is directed northward, almost perpendicular to the ecliptic, and thus provides a two dimensional (ecliptic plane) distribution. The resolution of the instrument is such that it takes a single 3 second snapshot every 84 seconds. Data from this instrument can be used to determine the density of the plasma, the electron temperature and the components of the plasma flow in the ecliptic plane.

The magnetic field measurements were made by the Jet Propulsion Laboratory vector helium magnetometer (Frandsen et al., 1978), which measures 3 orthogonal magnetic field components at a rate of six field vectors each second. However, the data in this chapter are presented in the form of 64 second averages.

Finally the measurements of the energetic ions are taken from the Energetic Particle Anisotropy Spectrometer (EPAS) (Balogh et al., 1978, van Rooijen et al., 1979), built by an international consortium comprising the Blackett Laboratory, Imperial College, London, the Space Science Department of ESTEC, Noordwijk, and the Space Research Laboratory, Utrecht. This instrument was originally designed to make accurate determinations of the proton distribution function in the solar wind upstream of the Earth, by making measurements of the angular distribution of the particle fluxes and their energy

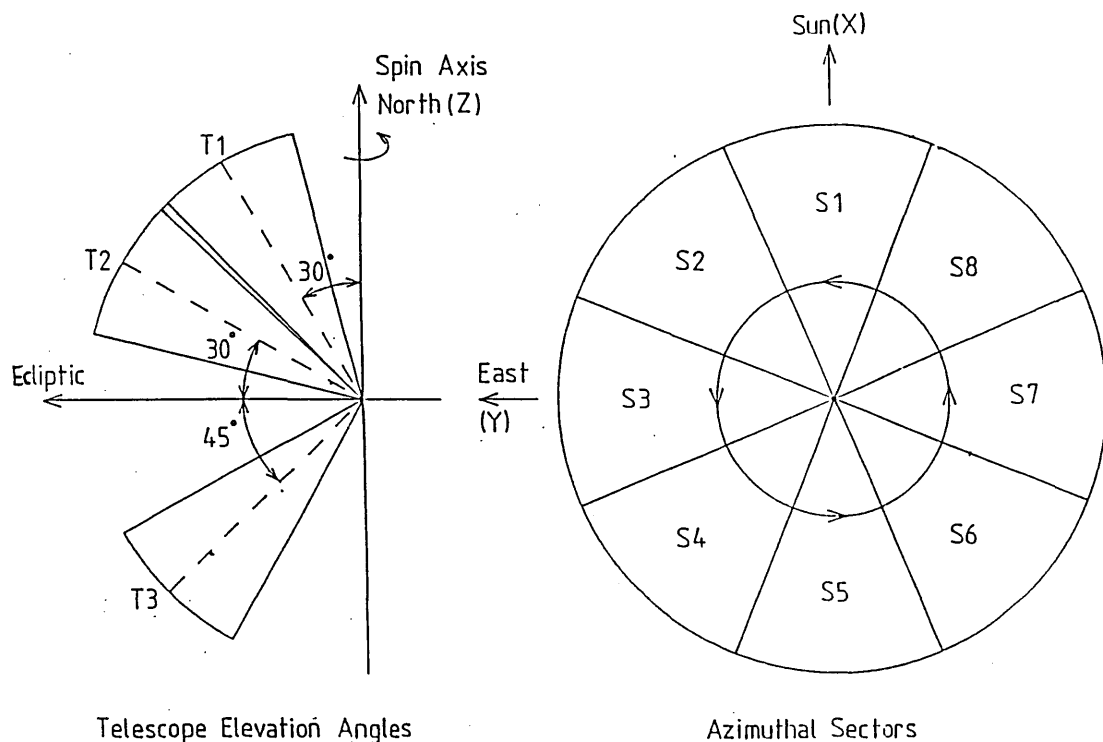


Figure 3.1. Schematic diagram illustrating the angular coverage of the EPAS instrument. The instrument measures ion fluxes in three dimensions in velocity space using a system of three identical semiconductor detector particle telescopes inclined at 30° , 60° , and 135° to the spacecraft spin axis, which is represented by the vertical line in the left hand panel, and points northward, perpendicular to the ecliptic plane. Each of these telescopes has a full viewing cone of 32° centred on the telescope look direction, which are represented by the conic sections in the left hand panel. As the spacecraft spins, the ion events detected by each telescope are stored in one of eight 45° azimuthal sectors (right hand panel). Sector 1 represents the sunward look direction, such that the sun is at the top in this diagram. A total of 24 directional flux measurements are thus recorded for each spacecraft spin period of 16 seconds..

spectrum. In order to do this with a reasonable degree of accuracy, the instrument detects ions in eight logarithmically spaced energy channels covering the range 35 to 1600 keV (although we shall confine our interest to the lowest 2 channels ($E < 95$ keV), where contamination from heavier ions is not significant), and the angular coverage is provided by three identical particle telescopes which are inclined at angles of 30° , 60° , and 135° to the spacecraft spin axis. These are illustrated in the left hand panel of Figure 3.1, where the spin axis is represented by the vertical line, whilst the look directions of each of the telescopes (numbered as indicated) are represented by the dashed lines. The conic sections about each look direction indicate the polar extent of the telescope fields of view ($\pm 16^\circ$ about the centre). The particle events are accumulated, for each energy channel and telescope, into eight 45° -wide azimuthal sectors as the spacecraft spins about its axis, as shown in the right hand panel of Figure 3.1. The sectors are numbered anticlockwise from Sector 1, which is defined by the sunward look direction. This gives one 24-point angular distribution (3 telescopes by 8 azimuthal sectors) for each energy channel every 16 seconds. This angular coverage allows the particle distribution function to be determined in terms of a spherical harmonic distribution, up to and including second order terms (Sanderson and Hynds, 1977). However the particular configuration of the magnetic field in the lobes, where the field direction is known to a high degree of certainty, makes such a treatment somewhat redundant. The zeroth order term of the spherical harmonic distribution can be used to determine the omnidirectional ion flux, but further information on the distribution can usefully be obtained by considering particle counts registered in various individual telescope/sector combinations, as we shall now explain.

The magnetic structure of the deep geomagnetic tail is such that the field points almost directly towards the Earth to the north of the central current sheet, and almost directly away to the south, and lies closely parallel to the ecliptic plane in both cases (Tsurutani et al., 1987). The only exception to this occurs in the region of the tail current sheet itself, where the component of the field transverse to the sheet drops to zero as it reverses in direction. As a result, the look directions corresponding to telescope 2 sectors 1 and 5 are those which look most closely along the field lines, and consequently detect the most field aligned particles (actually those with pitch angles approaching 14° and 166°). Note that these limits are set by the geometry of the EPAS instrument, which

precludes measurement of 0° and 180° particles in this case). Sector 1 of telescope 2 views in a cone centred at 30° above the ecliptic plane and in a generally Earthward direction (negative GSE x-direction), and as such will detect ions streaming tailwards along the field, whilst sector 5 views 30° above the ecliptic in the positive GSE x-direction, and detects Earthward streaming ions. The information about the streaming of ions in a tailward or Earthward direction along the field is important in the context of the tail, since it indicates the direction in which the ions are being accelerated, and thus indicates the relative position of the neutral line to the spacecraft. The energetic ions in the plasma sheet have also been shown to convect with the thermal plasma, such that estimates of the bulk ion velocity $\underline{v}$, density n_i and temperature T_i , can be made by fitting a convecting Maxwellian to the observed distribution (Richardson et al., 1987). The ion bulk velocity may then be used to infer a second value of the plasma sheet flow speed, that may be compared to that determined by the thermal electron instrument described above.

Conversely, sectors 3 and 7 of all the telescopes look closely perpendicular to the field direction and therefore detect those particles which have pitch angles close to 90° . For the particular field configuration that is found in the tail the widest range of pitch angle that is sampled by a single telescope is therefore collected by telescope 2, and this will be an important factor when we consider the distribution of energetic ions in the deep tail lobes in Chapter 5. However there are six combinations of telescope and sector which should result in the detection of particles with pitch angles close to 90° in the deep tail. These ions are useful in that they may be used to probe density gradients and boundary layers in the tail. Information from the turn on/off times of ion enhancements in each of the 6 telescope sectors detecting 90° pitch angle particles may be used to infer both the speed at which a particular boundary between two plasma regimes crosses the spacecraft location, and the orientation of that boundary relative to the spacecraft (Richardson and Cowley, 1985). This then gives a useful insight into the geometry of the regimes under consideration, and their motion relative to the spacecraft.

Having described the instrumentation on ISEE-3, and briefly discussed some analysis techniques, we shall now move on to examine the CDAW-8 Event A in some detail.

3. The Substorm Event of 28th January 1983 - ISEE-3 Particle and Field Observations.

An overview of the field and particle observations made by ISEE-3 during the CDAW-8 Interval A (0400 - 1100 UT on January 28th 1983) is shown in Figure 3.2. At this time the spacecraft was located some 216 R_E downstream from the Earth. The upper panel shows the EPAS energetic ion data, beginning at the top with the direction averaged ion intensity, at full 16 second resolution, for the lowest energy channel (35 - 56 keV). Next the 35 - 56 keV ion fluxes from telescope 2, sectors 1 and 5 are shown, i.e. those telescope sectors which best detect the tailward- and Earthward-streaming ion fluxes respectively. Below this the ratio R of these two fluxes is plotted, giving a measure of the relative intensities of the tailward- and Earthward-streaming ions. The final 3 plots in this upper panel show the energetic ion bulk speed and direction, which are derived from the assumption that the observed ion anisotropies arise from the convection of the ions with the thermal plasma, such that they may be accurately fitted with a convecting Maxwellian distribution (Daly et al., 1984, Richardson et al., 1987). In these plots θ represents the polar angle of the derived flow, such that $\theta = 90^\circ$ indicates a northward directed flow, $\theta = 0^\circ$ indicates a flow completely confined to the ecliptic plane, whilst ϕ is the azimuthal angle, such that $\phi = 0^\circ$ indicates a flow directed towards the Earth, and $\phi = 180^\circ$ a flow directly away from the Earth. The middle panel of the figure shows the plasma parameters which are derived from the Los Alamos thermal electron data. From top to bottom these show the plasma number density, electron temperature and ecliptic plane bulk speed and azimuth ϕ , which has the same convention as the azimuth of the ion flow direction of the top panel. The bottom panel of Figure 3.2 shows the magnetic field data, the first plot showing the magnetic field strength during the period, whilst the lower two plots indicate the direction of the field. Following the convention employed for the energetic ion flow directions, θ represents the polar angle of the field, such that $\theta = 0^\circ$ indicates a field lying completely in the ecliptic plane, whilst ϕ is the azimuthal angle, such that $\phi = 0^\circ$ indicates a field pointing towards the Earth (as expected in the north lobe), and $\phi = 180^\circ$ a field pointing directly away from the Earth (expected in the south lobe).

During the interval under consideration here, ISEE-3 encountered a number of distinct regions of the distant tail and its environs. Since the motion of the spacecraft relative to the Earth is negligible on the temporal and spatial scales

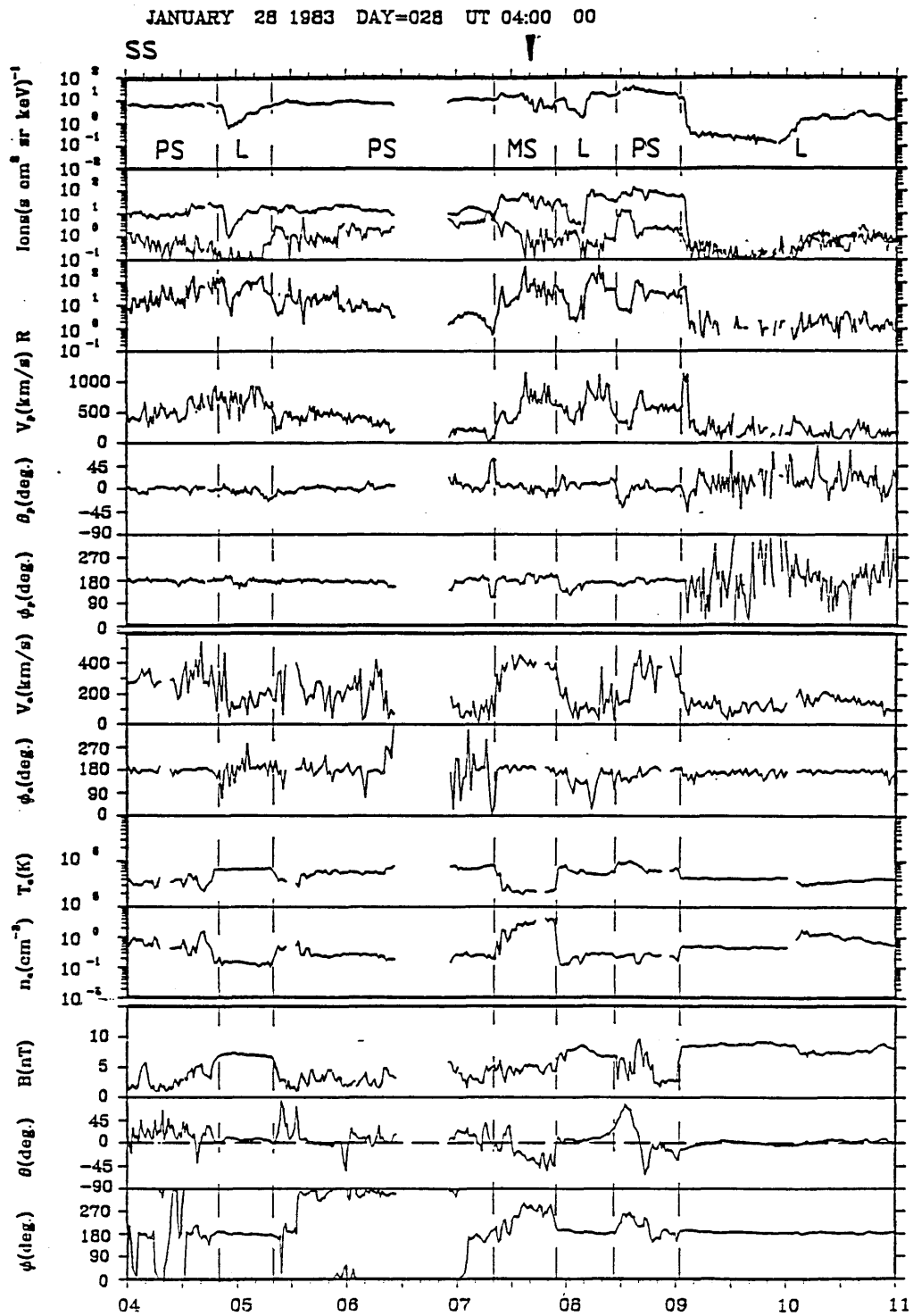


Figure 3.2. ISEE-3 data for the period 0400 to 1100 UT on the 28th January 1983, when the spacecraft was located at GSM coordinates (-216, 3, -7) RE. The top panel shows the EPAS energetic ion data, from the top, the 35-56 keV direction averaged ion intensity, the tailward and Earthward directed 35-56 keV ion intensities and their ratio R , and the ion bulk flow velocity V_p and direction θ_p and ϕ_p . The Los Alamos electron plasma temperature density and ecliptic plane flow speed and azimuth are shown in the central panel, while the JPL magnetic field GSM direction and magnitude are in the bottom panel. The enhancement in geomagnetic activity (see Figure 3.3) is indicated by the arrow at the top of the figure. The regions encountered by the spacecraft are indicated in the top panel (PS = Plasma sheet, L = Lobe, MS = Magnetosheath).

involved, this is due to either large scale displacements of the entire tail ("tail flapping") resulting from changes in the solar wind conditions (Hones et al., 1984), or to restructuring of the tail in response to changing geomagnetic conditions, which we shall be discussing below. The principle regions which are encountered by the spacecraft are labelled in Figure 3.2, and the vertical dashed lines indicate the times at which the spacecraft crossed the boundary between two adjacent regions. The magnetosheath (labelled MS) is characterised in the plasma data by relatively high densities ($>1 \text{ cm}^{-3}$), and a temperature which is typically lower than those which are observed in the tail, and a tailward ($\phi \approx 180^\circ$) flow at speeds comparable to those observed in the solar wind ($V \approx 400 \text{ km s}^{-1}$). Both the magnetic field strength and direction in this region are usually highly variable, as is the omnidirectional flux of the energetic ions, which may vary in intensity by up to an order of magnitude over time scales of a few minutes. In contrast, the tail lobes (L) are characterised by much stronger ($B \approx 10 \text{ nT}$) and steadier fields which point either directly towards (north lobe) or away (south lobe) from the Earth ($\phi = 0^\circ$ and 180° respectively). The plasma electrons in this region show lower densities, higher temperatures, and lower tailward bulk flow speeds than those observed in the magnetosheath, whilst the energetic ion fluxes are also much reduced, except in the region immediately adjacent to plasma sheet, where plasma sheet-like ion fluxes are found in lobe-like plasma and field regimes. This is the plasma sheet boundary layer formed by energetic ions streaming out ahead of the thermal plasma on reconnected field lines, as discussed in the last chapter. Finally the plasma sheet (PS) itself is generally (but not unfailingly) typified by comparable densities, but somewhat higher temperatures than those observed in the tail lobes. The field strength, however, tends to be depressed relative to the lobes due to the diamagnetic effect of the plasma, and is often variable in both magnitude and direction. The plasma flow in the sheet is generally tailward in the distant tail, and the flow speeds may vary over a range from a few hundred to $>1000 \text{ km s}^{-1}$ (Richardson et al., 1987).

Before moving on to describe the distant tail observations made by ISEE-3, it is instructive to outline the prevailing geomagnetic conditions for this period. A full global study of these conditions has been made by Baker et al., 1988, and we shall briefly summarize these authors' observations here. The level of geomagnetic activity during this period is indicated in the auroral electrojet indices shown in Figure 3.3. For the first few hours of this period the level of

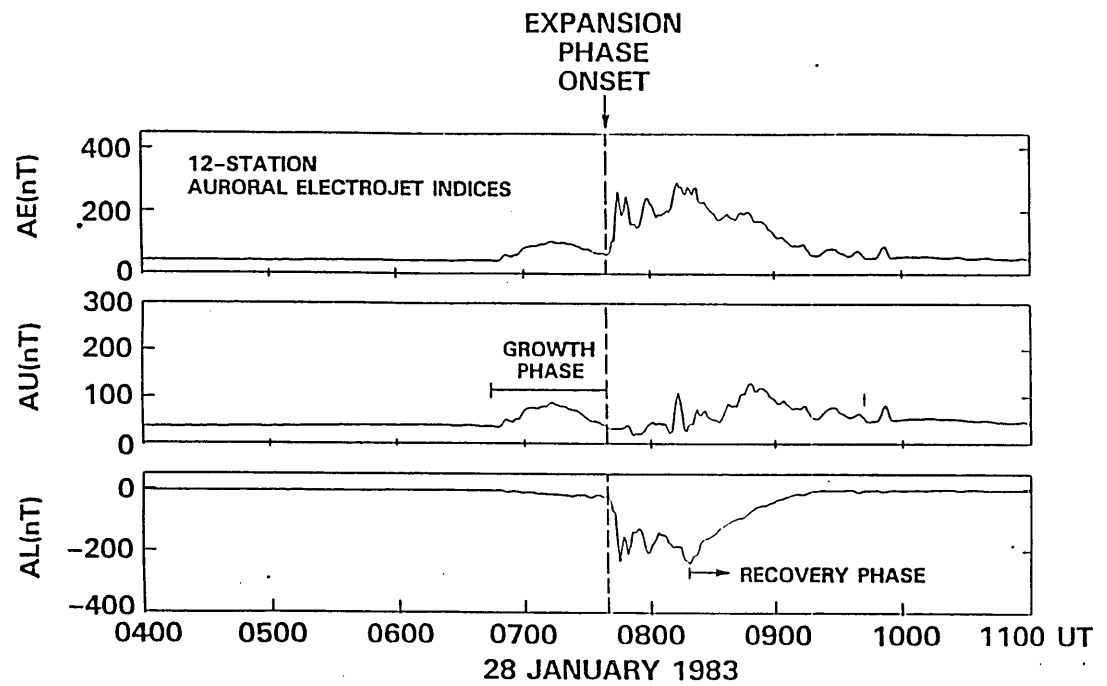


Figure 3.3. The AE, AU, AL auroral electrojet indices, indicating the level of geomagnetic activity, for the period 0400 to 1100 UT on the 28th January 1983. The times of substorm growth, expansion, and recovery phases are indicated. The vertical dashed line is the expansion phase onset, occurring at ≈ 0740 UT (from Baker et al., 1988)

geomagnetic activity was extremely low, due for the most part to the fact that the interplanetary magnetic field (IMF) B_z component had been northward for several hours before the start of this period. At 0616 UT the IMP-8 spacecraft, located at 38 R_E upstream from the Earth, detected a southward turning of the IMF B_z , which became progressively larger over the next 10 or so minutes, reaching 5 nT by 0630 UT. Such a change in the solar wind conditions is likely to reach the nose of the magnetosphere approximately 8 minutes later, when the onset of dayside reconnection becomes a possibility. This would lead to addition of magnetic flux and energy to the geomagnetic tail, which is known as the "growth phase" of a substorm. The AL index, which is an indicator of the development of the westward electrojet shows a slight decrease before about 0740 UT. However, the AU index, a measure of the eastward electrojet and the development of currents associated with the substorm growth phase, shows substantial enhancements after 0640 UT. The AE index, which is the magnitude of the difference between AU and AL also shows this development (due to AU) at this time. At 0738 UT there is a rapid drop in the AL index (and an associated rise in AE), which is characteristic of a substorm "expansion" phase onset. At approximately the same time the AFGL magnetometer network detected a burst of Pi2 activity, several geostationary satellites detected particle injection events, ISEE-1 (located at the dawn magnetopause) observed auroral kilometric radiation, and the DE-1 auroral imager discerned a substantial brightening of the aurorae in the midnight sector (Baker et al., 1988). All of these observations are indicative of the occurrence of a single isolated substorm whose expansion phase began shortly before 0740 UT. The auroral indices show that the recovery of this substorm began somewhere between 0820 and 0840 UT (depending on which index is used), and was largely complete by about 0915 UT.

Turning now to the ISEE-3 data, we shall concentrate first on the quiet time interval which lasts from the start of the interval at 0400 UT until about 0730 UT. Figure 3.2 shows that the spacecraft was located for most of this period in the tail plasma sheet, where both the plasma and energetic ion flows are consistently tailward. The spacecraft makes a brief exit through the plasma sheet boundary layer and into the southern lobe at about 0500 UT. Within the boundary layer the energetic ions are observed to stream unidirectionally tailward. Recalling the theoretical origin of this layer described in the last chapter, this strongly suggests that the layer, and by implication the adjacent

plasma sheet, was located on reconnected field lines some distance tailward of the neutral line. There exists no apparent mechanism by which such a unidirectional, field aligned flow of energetic ions could be formed and maintained on closed field lines.

The speed and orientation of the boundary layer across the spacecraft location may be deduced from the fluxes of 90° pitch angle particles as indicated in the previous section. This analysis was not possible during the spacecraft exit into the lobes, since a gradual change in the fluxes of 90° pitch angle particles precluded accurate determination of the turn off time of these particles, but on reentry the layer was found to have moved downward ($\psi = 278 \pm 4^\circ$) over the spacecraft at a speed of $23 \pm 7 \text{ km s}^{-1}$ (ψ is the direction of motion of the boundary (normal to the plane of the boundary) in the GSE y-z plane, such that $\psi = 0^\circ$ denotes northward motion, $\psi = 90^\circ$, motion towards dusk). The plane of the boundary in this case was extremely distorted, lying almost exactly north-south, indicating that a large scale twisting of the tail had occurred, resulting in the structures being rotated through 90° from their nominally expected positions. The observed speed of the layer, combined with the duration of the encounter indicates that its thickness was of order $5 R_E$. Note that the lack of geomagnetic activity during this early period suggests that this motion of the spacecraft relative to the tail structures resulted from large scale motion of the tail as a whole, rather than restructuring during a substorm.

Although the flows in the boundary layer suggest a spacecraft location at some point tailward of the neutral line, the observed properties of the plasma sheet do not agree with those expected, and described in the last chapter, on the basis of typical lobe parameters. In the last chapter a value for the tailward plasma sheet flow speed v_{OT} of 1150 km s^{-1} was obtained, whilst both the directly measured thermal electron flow speed and the inferred energetic ion bulk speed show flow speeds of around 300 km s^{-1} . Also, the model presented in the last section suggests that the quiet time plasma sheet in the deep tail would be of order $1.3 R_E$ (assuming the spacecraft is located at a distance of $100 R_E$ from the neutral line), such that the encounter time at the speeds with which the layers are observed to move would be ≈ 5 minutes. The extended nature of the encounters with the plasma sheet (≈ 1 hour) therefore suggest a much thicker sheet in this particular case, a result which is supported by the observation of a $\approx 5 R_E$ thick boundary layer. Equations 2.9 - 2.12 of the last chapter suggest that the energetic ions should occupy almost all of the reconnected field wedge,

whilst the plasma sheet particles occupy somewhat less than half, being confined to the central portion. On this basis the full thickness of the plasma sheet may be inferred to be about twice the thickness of the boundary layer (the region occupied by the energetic particles outside the plasma sheet itself). We thus infer a plasma sheet thickness of $\approx 10 R_E$ in this case, a value which is more compatible with the extended nature of the encounter.

The apparent discrepancy between the values predicted in the last chapter and those observed in this case may be resolved by noting that the plasma parameters in this particular case are considerably different from those typical values used in the theoretical work. In particular, this period is notable for the unusually high value of the plasma sheet density (and by implication the density of its source plasma in the lobes), combined with a rather low value of tail field strength. These values ($\approx 0.5 \text{ cm}^{-3}$ and 7 nT compared with typical values of 0.1 cm^{-3} and 10 nT) give a plasma sheet Alfvén speed $V_A \approx 150 \text{ km s}^{-1}$ (equation 2.5). Together with a lobe bulk speed of about 100 km s^{-1} for this period, the theory suggests that the plasma sheet outflow speed tailward of the neutral line (equation 2.7b) should be $\approx 400 \text{ km s}^{-1}$. Considering that the theory completely neglects the effects of heating of the plasma during its interaction with the current sheet, this is perhaps not a bad correspondence with the observed values. Using the observed values of plasma sheet flow speed and lobe field strength, together with the assumptions made in the theory section that the quiet time cross tail electric field, (E_y) is 0.1 mV m^{-1} (resulting from a cross tail potential of 30 kV across a $50 R_E$ wide tail, e.g. Cowley, 1984a), and that the neutral line is located at $100 R_E$ downtail from the Earth, and further assuming that the field line contraction speed is half that of the plasma sheet particles, we obtain a full plasma sheet thickness (c.f. equation 2.11) of $11.5 R_E$. This figure is compatible with the rough estimate made on the basis of observations above. The plasma and energetic ion characteristics of the quiet time plasma sheet between 0400 and 0535 UT are therefore consistent with the spacecraft location tailward of the neutral line, and approximately fit the predictions of the model of the last chapter, if account is taken of the unusual lobe conditions during this time. This indicates that the deep tail plasma sheet is not always fast flowing and thin, as was expected on the basis of the predictions from the 'typical' values employed in the last chapter.

One further difficulty with the interpretation of this section of data in terms of the model presented in the last chapter concerns the average northward tilt of the field during this quiet period (see the bottom panel of Figure 3.2). The model predicts, for this case, that the field should have a component of about 0.4 nT threading through the plasma sheet, in a direction from the north to south lobe. However, as explained above, the tail appears to have been twisted through about 90° during this period, such that the implication of the observed northward tilt is not clear.

During the later part of this quiet time interval it is likely that the spacecraft is moving through the plasma sheet in the direction of the tail magnetopause, as is evidenced by its eventual exit into the sheath directly from the plasma sheet at about 0720 UT. From about 0535 UT the plasma sheet flow speed (as seen most clearly in the energetic ion bulk speed) begins to decline, such that it reduces to values of 100 km s^{-1} in both the ion and thermal electron data just prior to crossing the magnetopause. These low flow speeds cannot be explained on the basis of the model presented in the last chapter, especially since the plasma number density also declines (to 0.3 cm^{-3}) leading to an increase in the Alfvén speed, and thus the expected plasma flow speed, during this period. This suggests the existence of a separate "slow plasma sheet" regime on the flanks of the tail between the magnetopause and the reconnection associated plasma regimes. This region may be accounted for by assuming that the layer is located on closed Earth-connected field lines that are convected tailwards, against the field tension, by some form of "viscous" momentum transfer from the magnetosheath. The density and temperature within this region are essentially the same as those observed in the reconnection-associated plasma sheet, which indicates there is little admixture of the denser, cooler plasma from the magnetosheath. The "viscous" process thus transfers momentum, but not mass, into the tail, which rules out the impulsive penetration models presented by Heikkilä (1982,1987) from being significant here. Some process such as the ideal Kelvin-Helmholtz instability (Southwood, 1979) is more likely, although there is no evidence for the waves associated with this instability in this data set. This "slow plasma sheet" phenomenon is also observed in two of the other CDAW-8 events, and the presence of closed field lines along the flanks of the deep geomagnetic tail has previously been reported by Slavin et al. (1985). These authors interpreted their observations as evidence for a curved tail neutral line which is closest to the Earth near local

midnight, and curves away from the Earth towards the dawn and dusk sides of the tail.

Having discussed the structure of the distant tail during the period of quiet geomagnetic activity, we shall now move on to study the response of the tail to the substorm whose expansion phase onset occurred shortly before 0740 UT, as discussed above. At this onset time the spacecraft was located in the magnetosheath (following its exit from the plasma sheet at 0720 UT), and its return to the southern lobe at 0755 UT is probably aided a substorm associated enhancement to the tail flux, caused by the onset of reconnection at the dayside magnetopause. Such flux should take about 1 hour to reach ISEE-3, assuming that it is convected from the nose of the magnetosphere to the deep tail at the solar wind speed. The entry into the tail lobe at 0755 UT therefore implies that the production of this flux began prior to 0655 UT, which closely agrees with the timing of the substorm growth phase, discussed above.

At 0810 UT, 15 minutes after ISEE-3 entered the lobe, and some 30 minutes after the onset of the substorm, there commenced a series of events which, in line with the theory discussed in the last chapter (c.f. Figure 2.5), may be interpreted as the passage of a plasmoid structure over the spacecraft location. At this time the spacecraft entered the plasma sheet boundary layer once more, and simultaneously detected the start of a northward tilting of the field. At 0828 UT ISEE-3 entered the plasma sheet itself (or in this case the plasmoid), where the field was observed to rotate first strongly northward, and then strongly southward. The southward field tilt declined to smaller, and steadier values after 0845 UT, which indicates an exit from the plasmoid into the "post plasmoid" plasma sheet. The spacecraft then exited back into the boundary layer at 0902 UT, and then returned to the south lobe at 0905 UT. Comparing these observed events with the predictions of the phenomenological substorm model described in the last chapter, it can be seen immediately from Figure 2.5 that the same general sequence of events (lobe, boundary layer, plasmoid, post plasmoid plasma sheet, boundary layer, lobe) occurs theoretically for a spacecraft located between about 1 and 5 R_E of the tail centre plane. The precise timings of the events of course depend on the assumed conditions, and on the motion of the tail as a whole relative to the spacecraft, but to a first approximation at least the theory can reproduce the observed features of the substorm in the deep tail.

We may study the events of this period more closely using the information obtained from the analyses of the energetic ions data (Figure 3.2). At 0810 UT, as the spacecraft entered the boundary layer, the edge of this region of enhanced ion intensity moved southward and dawnward ($\psi = 135 \pm 5^\circ$) across the spacecraft at a speed of $37 \pm 5 \text{ km s}^{-1}$. The ions in the layer are observed to stream unidirectionally tailward, consistent with them being located on reconnected field lines tailward of the neutral line. On the basis of the theory presented in the last chapter, we surmise that the entry of the spacecraft into this layer is due (neglecting large scale tail motion) to the combined effects of the layer broadening in spatial extent (resulting from an increased reconnection rate at a neutral line much further Earthwards than previously), and to the displacement of the layer due to the passage of the leading edge of the plasmoid structure at positions closer to the tail centre plane. This is supported by the spacecraft's subsequent entry into the plasmoid itself, which is marked by a sharp fall in the ratio R of the tailward- and Earthward-streaming ions, together with the bulk speed inferred from the ions. These reflect the change in the ion characteristics from a free streaming population moving along the open reconnected field lines in the boundary layer, to an isotropised population which has a broader distribution, and is convected with the thermal plasma (Richardson and Cowley, 1985, 1987; Richardson et al., 1987). The ion flow speeds in the plasmoid are observed to be around 400 km s^{-1} . Again this is slower than the speed assumed in the theory on the basis of statistical studies of plasmoid speeds, but is in line with the overall slowness of the plasma sheet during this interval, as discussed previously. Combining the duration of the spacecraft encounter with the plasmoid, together with its implied speed, gives a plasmoid length of $65 R_E$. However, the earlier northward tilt in the field suggests that the leading edge of the plasmoid passed the spacecraft (but closer to the tail centre plane) some 10 minutes before actual entry, so that this figure may more realistically be put at $95 R_E$. This is in reasonable agreement with the assumptions made in the last chapter, but is actually somewhat longer than the average length of a single looped plasmoid, which was found to be $60 R_E$ by Richardson et al. (1987).

Within the post plasmoid plasma sheet (0845 - 0902 UT) flow speeds are again observed to be less than those predicted from the model using "typical" lobe parameters, at about 400 km s^{-1} . However, using the observed values ($B = 8 \text{ nT}$, $n = 0.3 \text{ cm}^{-3}$, $v_i = 100 \text{ km s}^{-1}$) we expect theoretically an outflow

speed of 550 km s^{-1} (equations 2.5, 2.7), again not inconsistent with observation, considering the theory takes no account of plasma heating. Further, assuming the substorm reconnection rate of 0.4 mV m^{-1} (e.g. Cowley, 1984a), and a neutral line to spacecraft distance of 180 R_E (as in chapter 2), we expect the post plasmoid plasma sheet to have thickness 22 R_E (equation 2.11), which is more than sufficient to account for the ≈ 20 minute encounter with this region. At 0902 UT the spacecraft moved into the boundary layer once more, where again the ions were observed to stream freely tailwards on lobe-like field lines, and then into the south lobe. The boundary layer is observed to move rapidly northwards ($\psi = 346^\circ$) at 213 km s^{-1} at this time. The spacecraft remained in the lobe until after the end of this period of data; the enhancement in ion intensity after 1000 UT is possibly due to a further encounter with the plasma sheet boundary layer without an entry into the plasma sheet itself. However, the slight increase in plasma density, and decrease in electron temperature, together with the lack of the strong tailward streaming of energetic ions which are characteristic of the boundary layer, suggest that the spacecraft may have moved close to the magnetopause at this time. The observed particle populations must then have leaked into the lobes across a magnetically open magnetopause, which accounts for the sheath like characteristics of the plasma.

This "disturbed" period within the CDAW Interval A thus exhibits all the responses of the deep tail to substorm activity as expected on the basis of the phenomenological substorm model produced in the last chapter. Increase in the size of the tail during the substorm growth phase is presumably responsible for the spacecraft entry into the tail lobe from the magnetosheath. The plasmoid structure was then observed to arrive at the spacecraft location some 40 minutes after the expansion phase onset, a delay which implies a mean downtail speed of $\approx 300 \text{ km s}^{-1}$ for the plasmoid. This figure is in reasonable agreement with the observed in situ plasma speed of $\approx 400 \text{ km s}^{-1}$, if allowance is made for a delay in plasmoid disconnection from the near-Earth plasma sheet after onset, and acceleration of the structure that may have occurred during its downtail motion. After the passage of the plasmoid tailward of the spacecraft, a thick post-plasmoid plasma sheet was observed for about 20 minutes, before the spacecraft moved back through the boundary layer into the tail lobe. This latter motion is presumably due in part at least to recovery-phase thinning of the deep-tail plasma sheet.

4. Discussion and Summary.

In this chapter we have studied a period of seven hours of tail data from one of the events chosen for study as part of the CDAW-8 workshop, although for our purposes we have interpreted the data in a manner that may be readily compared to the predictions of the theoretical work, and the phenomenological substorm model produced in the last chapter. The event is characterised, in terms of prevailing geomagnetic conditions, by an extremely quiet period at the start of the interval, followed by clear signatures of the growth-, expansion-, and recovery phases of a single, isolated substorm in several ground and near-Earth data sets. During the initial quiet period the ISEE-3 spacecraft, located in the deep tail, spends a protracted period of time in the plasma sheet and its boundary layer, where the plasma is observed to stream tailwards, indicating that ISEE-3 is tailward of the neutral line. The length of time spent in the plasma sheet is interpreted as evidence for a thick plasma sheet, which is initially in contradiction with the thin plasma sheet predicted from theory, as is the general slowness of the plasma sheet flows at this time. However, if the theoretical values are recalculated using the "untypical" values of lobe field strength and density prevailing during this period, a reasonable agreement with observation is reached, especially if the limitations of the theory are borne in mind. This indicates that the reconnection rate and the distance from the neutral line are not the only relevant parameters, but that the lobe field strength and density may also have significant effects on the structure of the plasma sheet and the flow speeds within it.

The latter half of the quiet period is characterised by extremely slow plasma flows which cannot be explained in terms of the theoretical work. The data indicates that this phenomenon occurs in a region of the plasma sheet which is adjacent to the tail magnetopause, and we surmise that this is the result of some form of viscous interaction which transfers momentum (but not mass) between the magnetosheath flow and that part of the plasma sheet which is located on closed field lines, such that this plasma is convected tailwards against the tension of the field. There is no evidence in this data set to indicate the exact mechanism by which this is achieved, although two similar periods in other CDAW-8 intervals are suggestive of the Kelvin-Helmholtz instability, as will be discussed below.

During the disturbed part of this period, we note that a well defined sequence of events occurs, during which the spacecraft encounters a plasmoid and associated post plasmoid plasma sheet. The timings of the events fit well with the time of expansion phase onset, and the period is readily interpreted in terms of the phenomenological substorm model presented at the end of the last chapter, given the particular conditions which apply at this time. Overall we feel that the assertion made at the end of the last chapter that the theoretical models form a useful basis on which the behaviour of the time-dependent tail may be understood is readily borne out by this interval of data.

The event described above is one of eight that were selected for study in the CDAW-8 workshop. A full discussion of each event, along the lines of the one presented in this chapter, can be found in Richardson, Owen, Cowley et al., 1988. The combined events represent the first multi-instrument case study of distant tail data covering a wide range of geomagnetic conditions, from extended intervals of magnetic quiet with isolated substorms (e.g. the event described above), to prolonged periods of intense disturbance. As a consequence of the wide range of prevailing conditions, this paper has brought to light a number of new features, as well as confirming and extending some previous results, which we shall summarise in the remainder of this chapter.

The first, and most important, result concerns the origin of the plasma sheet observed in the distant tail. On the basis of combined CDAW-8 observations it appears, for the most part, that the plasma sheet at distances of 100 to 200 R_E is associated with reconnection at a neutral line lying at a position closer to the Earth. This is evidenced by the good agreement which is generally obtained between the observed plasma sheet flow speed and the expectations based on stress balance on the reconnected field lines, with the notable exception of the "slow plasma sheet" regimes. The agreement is such that the theoretically derived values are usually within 100 km s^{-1} of the observed values, despite variations in the latter of between $\approx 300 \text{ km s}^{-1}$ and $\approx 900 \text{ km s}^{-1}$. The plasma sheet flow speeds frequently exceed the speeds observed in the adjacent magnetosheath, sometimes by a large factor, which rules out any explanation of the plasma sheet origin in terms of a "viscous" interaction at the magnetopause in these cases. Further evidence supporting a reconnection origin is provided by the observation of spatially dispersed boundary layers of energetic ions which stream unidirectionally along lobe-like field lines just outside the plasma sheet, as is expected from the reconnection theory. The CDAW-8 data set also

contains one quiet time example in which the tail neutral line clearly propagated past the spacecraft, which was located at about 220 RE, leading to a reversal in the flow direction of the energetic ions and plasma sheet plasma from tailward to Earthward. Within the region of earthward flow an isotropic energetic electron population was observed, consonant with expectations for a trapped population on closed field lines, whereas, in the region of tailward flow observed shortly before, the energetic electrons were below background fluxes. This reflects the magnetically open nature of the latter region, which can lead to efficient evacuation of the energetic electrons from the plasma sheet.

Despite the strong support for the reconnection origin of the plasma sheet, there are three periods of low or intermittent geomagnetic activity which contain extended plasma sheet intervals in which the plasma density and temperature are typical of the plasma sheet, but the plasma bulk speed, directed tailwards, is too low (100 to 200 km s⁻¹) to be explained on the basis of stress balance tailward of the neutral line. These results suggest the presence (but not the exclusive presence) of a tailward-flowing "viscously-driven" layer of closed flux tubes (which are indicated by the observation of isotropic energetic electron fluxes in two of the three cases, though not the one described above). These "slow plasma sheet" regimes are found to be located on the tail flanks, and are about 10 RE in both dimensions transverse to the tail axis.

With the exception of the bulk flow speed the plasma parameters observed during these periods do not differ significantly from the adjacent reconnection-associated plasma sheet, and differ markedly from those of the magnetosheath, which is much denser and cooler. This strongly suggests that these flux tubes originate in the hot plasma sheet region Earthward of the tail neutral line, which, following reconnection and an interval of earthward flow, eventually retreat tailward again under the action of "viscous" stresses imposed at the magnetopause. Since these flux tubes are devoid of magnetosheath-like plasma, the mechanism transferring momentum to this layer cannot involve transfer of mass, as suggested by e.g. Heikkila (1982). However, the two intervals containing "slow plasma sheet" regimes which were not discussed above, show evidence of boundary waves and vortices in the plasma sheet, which are suggestive of the Kelvin-Helmholtz instability operating at the magnetopause. This is in agreement with recent results presented by Sibeck et al. (1987a), who show evidence for the occurrence of Kelvin-Helmholtz waves at the distant tail magnetopause, and also with the magnetic field results of Slavin

et al. (1985), who presented evidence for a curved neutral line which would result in closed flux tubes adjacent to the magnetopause to as far tailward as 280 R_E.

The combined CDAW8 data set also provides further support for the neutral line model of substorms, though suggesting the need for some interesting developments. Evidence of tail expansion associated with the increased flux content and/or down-tail propagation of the plasmoid is present in several of the intervals, whilst direct encounters with plasmoids occur in four of the intervals. All the clear plasmoid encounters can be related to enhancements in geomagnetic activity, and their time of appearance in the deep-tail is compatible with disconnection from the near-Earth tail at the time of the enhancement. However, not all disturbance enhancements were followed by observations of plasmoids. Although it is likely that the spacecraft will, at times, not be favourably located to observe the passage of a plasmoid, it appears that some disturbance enhancements may be related to increases in the reconnection rate at the pre-existing near-Earth neutral line. In this case the plasma sheet would, on the basis of theory, be expected to expand, and may engulf a spacecraft located close to the tail centre plane, but no plasmoid would be produced. There is a clear example of such behaviour within the CDAW-8 data set, as well as several possible cases.

Finally, the combined data set supports the conclusion made above regarding the interval presented in this chapter, that the reconnection rate and location of the neutral line are not the only factors which influence the thickness of the plasma sheet, and that variations in the lobe field strength and plasma number density can be equally important. As a result of these additional factors there is no very clear-cut correlation between plasma sheet thickness and geomagnetic activity.

CHAPTER 4.

CURRENT SHEET STRESS BALANCE IN THE GEOMAGNETIC TAIL FOR ASYMMETRICAL TAIL LOBE PLASMA CONDITIONS.

1. Introduction.

In chapter 2 of this thesis we discussed models of the distant tail based upon the one-dimensional stress-balance approximation and extended the theory to include time-dependence of the reconnection rate and neutral line position. In that chapter (and also in previous work of this nature e.g. Cowley (1980, 1984), Cowley and Southwood (1980)) it was assumed for simplicity that the properties of the inflow plasma are symmetrical on either side of the current sheet. If one transforms to the rest frame of the reconnected field lines (de Hoffman and Teller (1950)) it is clear that in this case there can be no net flow along the field lines, when consideration is taken of both the plasma flowing into as well as out of the current sheet. As described in chapter 2, the equilibrium condition is then that the combined distribution outside the current sheet must satisfy the marginal firehose stability condition

$$P_{\parallel} - P_{\perp} = B^2/\mu_0 \quad (4.2)$$

(Rich et al., 1972; Eastwood, 1972, 1974; Hill, 1975).

However, recent observations in the distant tail have shown that substantial density differences, up to an order of magnitude or more, may exist between the plasma in the two tail lobes on either side of the current sheet (Gosling et al., 1985). Cowley (1981) demonstrated theoretically that the tailward flow speed of the lobe plasmas should be enhanced in regions of higher density, resulting in flow shear between the two lobes. There is some indication of this effect in the Gosling et al. (1985) data, but conclusive observational evidence has yet to be presented. However, for reasons of generality, we will assume here that such shears do exist between the lobe flows. The flow and density asymmetries are associated with IMF B_y , and arise from the east-west forces exerted on open field lines which cause them to be added to the northern lobe preferentially on the dawn side for B_y positive and on the dusk side for B_y negative, and vice versa in the southern hemisphere. Consideration of the expected density and down-tail bulk speed of the "mantle" plasma flowing in towards the tail centre after entering over the tail magnetopause then shows that for IMF B_y positive the lobe plasma should be denser and faster flowing in the north tail lobe than in the south on the dawn side, and vice versa on the dusk side, whilst the reverse is true for IMF B_y negative (Cowley, 1981). This expectation is in accord with the observed density asymmetries (Cowley et al., 1984; Gosling et

al., 1985). Only near the tail centre will densities and bulk speeds be generally similar in magnitude in the two lobes adjacent to the current sheet.

When lobe plasma asymmetries exist a net flow of plasma through the current sheet will generally occur and the equilibrium condition (equation 4.1) must be modified. Stress balance in this more general case has been studied e.g. by Francfort and Pellat (1976) and Sonnerup et al. (1981), it being shown, for example, that in the case of inflow from one side of the current sheet only, and transmission of all the plasma through the sheet, the field-aligned inflow speed of the plasma in the field line rest frame must be equal to the lobe Alfvén speed. In this more general work it has been customary to express results in terms of flows and pressure anisotropies as separate components in the stress balance equation. However, this distinction is rather artificial and can lead to unnecessary complexity in calculation because the velocities and pressures referred to are not those of the inflow plasma alone, but those of the combined distribution of inflow and outflow plasma together. Thus, for example, the stress (current distribution) due to a single plasma stream of given density and speed flowing through the current sheet (the limiting anisotropic case) is clearly the same as that due to two counterstreaming beams of the same speed but of half the density each (the symmetrical case), yet in the first case stress balance is described in terms of flow, while in the second it is described in terms of anisotropic pressure. Here we point out that the general stress balance condition can be written in a simple form in which the general parallel momentum flux $M_{\parallel}$ replaces $P_{\parallel}$ in equation (4.1). Since $M_{\parallel}$ is proportional to the integral of $v_{\parallel}^2$ over the combined particle distribution f its value depends only on the field-aligned speed of the particles, and not upon their direction of motion.

In the next section we will derive the simplified form of the stress balance equation, while in section (3) we will illustrate its utility by solving a simple example in which the tail lobe plasma is taken to form cold beams in both lobes, but of differing density and field-aligned speed.

2. The General One-Dimensional Stress Balance Condition

In this section we will derive the general equilibrium conditions for a one-dimensional current sheet given by the fields

$$\mathbf{B} = (B_x(z), B_y(z), B_z)$$

$$\mathbf{E} = (E_x, E_y, E_z(z)) \quad (4.2)$$

where B_z , E_x and E_y are all constants. We note that E_x and E_y may be removed by frame transformations in the y and x directions respectively, with speeds $-E_x/B_z$ and E_y/B_z , and in this section we will work in the transformed frame where E_x and E_y are zero. The derivation is essentially identical to that of e.g. Francfort and Pellat (1976) and Sonnerup et al. (1981), but the result is expressed in a simpler and often more convenient form. We will now outline the steps of the calculation (see also Cowley (1980)), in order that this chapter be self contained.

Integration of the first moment of the Vlasov equation over velocity space yields the steady-state equilibrium equation

$$\text{div} (\mathbf{M} - \mathbf{T}) = 0 \quad (4.3)$$

where $\mathbf{M}$ is the plasma stress tensor given by

$$M_{ij} = \sum_s m_s \int_{-\infty}^{\infty} d^3v v_i v_j f_s \quad (4.4)$$

(where m is the particle mass, f the particle velocity distribution function and s the species label), and $\mathbf{T}$ is the Maxwell stress tensor given by

$$\mu_0 T_{ij} = B_i B_j - \frac{1}{2} B^2 \delta_{ij} \quad (4.5)$$

assuming that electric field terms can be neglected. For a one-dimensional system equation (4.3) becomes

$$\frac{d}{dz} (M_{iz} - T_{iz}) = 0 \quad (4.6)$$

which integrates to give the three equilibrium equations

$$M_{iz} - T_{iz} = C_i \quad (4.7)$$

where the C_i are constants. Use of equation (4.5) then gives explicitly

$$M_{xz} - \frac{1}{\mu_0} B_x B_z = C_x \quad (4.8a)$$

$$M_{yz} - \frac{1}{\mu_0} B_y B_z = C_y \quad (4.8b)$$

$$M_{zz} + \frac{B^2}{2\mu_0} - \frac{B_z^2}{\mu_0} = C_z \quad (4.8c)$$

Outside the current sheet the particle distribution functions will be gyrotropic, so that in field-aligned coordinates the stress tensor will be diagonal, with components $M_{\parallel}$ and $P_{\perp}$ along and transverse to the field respectively, given by

$$M_{\parallel} = \sum_s m_s \int_{-\infty}^{\infty} d^3v v_{\parallel}^2 f_s \quad (4.9a)$$

and

$$P_{\perp} = \frac{1}{2} \sum_s m_s \int_{-\infty}^{\infty} d^3v v_{\perp}^2 f_s \quad (4.9b)$$

Outside the current sheet we then have

$$M_{ij} = (M_{\parallel} - P_{\perp}) \frac{B_i B_j}{B^2} + P_{\perp} \delta_{ij} \quad (4.10)$$

Denoting the two sides of the current sheet by the subscripts '1' and '2' and substituting equation (4.10) into equation (4.8), we obtain

$$(\alpha_1 - 1)B_{x1} = (\alpha_2 - 1)B_{x2} \quad (4.11a)$$

$$(\alpha_1 - 1)B_{y1} = (\alpha_2 - 1)B_{y2} \quad (4.11b)$$

$$P_{\perp 1} + \frac{B_1^2}{2\mu_0} + (\alpha_1 - 1)\frac{B_z^2}{\mu_0} = P_{\perp 2} + \frac{B_2^2}{2\mu_0} + (\alpha_2 - 1)\frac{B_z^2}{\mu_0} \quad (4.11c)$$

where

$$\alpha = \mu_0(M_{\parallel} - P_{\perp})/B^2$$

If we consider the solution of the pair of equations (4.11a,b) then either the fields in the plane of the current sheet must be exactly parallel or antiparallel (i.e. $B_{x1}/B_{y1} = B_{x2}/B_{y2}$), which will not in general be the case, or we must have

$$(\alpha_1 - 1) = (\alpha_2 - 1) = 0 \quad (4.12)$$

Thus the general equilibrium conditions are (in regions where the plasma is gyrotropic), from equations (4.12) and (4.11c)

$$M_{||} - P_{\perp} = B^2/\mu_0 \quad (4.13a)$$

and

$$P_{\perp} + B^2/\mu_0 = \text{constant} . \quad (4.13b)$$

Note that equation (4.13a) is of the same form as equation (4.1) but with $P_{||}$ replaced by $M_{||}$, as previously stated.

It is customary to express $M_{||}$ as the sum of flow and pressure components, i.e.

$$M_{||} = \rho V^2 + P_{||}$$

where ρ is the plasma mass density and V the field-aligned bulk flow speed. Hence (4.13a) becomes

$$\rho V^2 + (P_{||} - P_{\perp}) = B^2/\mu_0$$

from which one immediately recovers equation (4.1) when $V = 0$, and when the pressure anisotropy is zero $V = \pm B/\sqrt{(\mu_0 \rho)}$. However, for reasons discussed in the introduction to this chapter, expression (4.13a) is generally preferable.

As a definite example we may reconsider the 'symmetrical' adiabatic one-dimensional current sheet solutions set up by Cowley and Pellat (1979). Equilibrium solutions were investigated under the assumption that guiding centre particle motion remains valid throughout the current sheet, such that the particle distribution functions are also gyrotropic throughout. The problem then resolves into the question of whether adiabatically mapped particle distributions exist which can satisfy governing equations (4.1) and (4.13b) at

each point along the field lines. Particles within the system can be classified as either 'trapped' or 'free', with particles in the former class mirroring within the depressed field region of the current sheet, whilst those in the latter class pass once through the sheet from one side to the other. Clearly the particles in the 'free' distribution must satisfy equation (4.1) outside the current sheet, but it was shown that, in order to satisfy equations (4.1) and (4.13b) throughout, a trapped population must also be present whose distribution function can be calculated for a given 'free' population.

However, using equations (4.13a,b) it is obvious that the 'symmetrical' solutions found by Cowley and Pellat (1979) may at once be generalized to the asymmetric case. If, for example, using the method of Cowley and Pellat (1979), one constructs the trapped population appropriate to a given symmetrical 'free' population consisting of equal counterstreaming beams each of density n , then the latter may immediately be replaced e.g. by a single unidirectional beam having the same functional form (distribution with pitch angle) as before but with density $2n$, without affecting the required trapped population. The same argument clearly applies to cases intermediate between the 'single stream' and 'symmetrical' extremes i.e. the 'symmetrical' beams can immediately be replaced by similar beams having density $(1+F)n$ in one direction and $(1-F)n$ in the other, where $F < 1$, without affecting the required trapped population. In general, however the 'free' streams entering the current sheet from either side will have differing functional forms, requiring recalculation of the trapped populations in each case. This topic will not be pursued further here. Rather, in the next section we will consider the application of (4.13a,b) to the problem of asymmetrical cold beam inflow appropriate to the geomagnetic tail, and will discuss the resulting effects on the structure of the plasma sheet.

3. Stress Balance for Asymmetrical Cold Beam Inflow.

We will now use the results of Section 2 to derive the equilibrium conditions for the case, applicable to the geomagnetic tail, where the perpendicular plasma pressure is small compared to the pressure of the lobe magnetic field. The Gosling et al. (1985) data shows that this plasma pressure is sufficient only to cause variations of order 10% or less between the lobe field strengths (equation 4.13b), and thus may be neglected. Hence the plasmas flowing into the current sheet from either side may be approximated as cold beams of differing density

and field-aligned flow speed. We will also assume for simplicity that all particles incident on the current sheet are transmitted through it, and form cold beams in the outflow. These assumptions will certainly be valid if the particles behaviour in the current sheet is adiabatic, and we also note that in the asymmetrical dayside magnetopause system (where, however, the cold beam approximation is not generally valid) observation indicates that a large majority of incident magnetosheath particles are transmitted through the magnetopause (Sonnerup et al. 1981). The effects of scattering and reflection of particles from the current layer considerably complicate the problem and will not be treated here.

As a consequence of these assumptions we have $P_{\perp} = 0$ everywhere outside the current layer on either side, and hence from equation (4.13b) we must also have the same field strength B on either side, taken to be the field strength in the tail lobes. We also assume that the field is planar with $\mathbf{B} = (B_x(z), 0, B_z)$ and $\mathbf{E} = (0, E_y, 0)$, where, as before, E_y and B_z are constants. Finally we assume that the inflow plasma is spatially uniform in the x -direction and look for steady states. The effects of spatial gradients in the inflow plasma parameters, together with time dependence, can be incorporated using the methods of Cowley and Southwood (1980) and the methods described in Chapter 2 of this thesis respectively, but are not the focus of attention here.

In Figure 4.1 we show the basic field configuration envisaged, in which B_x reverses in sign across a current sheet (shown hatched) such that the reconnected field lines downstream from the neutral line (NL) form sharply bent hairpins. In the analysis below we will assume for simplicity that $|B_x|$ is much larger than $|B_z|$ outside the current sheet, as will usually be the case in systems of interest, although the results may be readily generalized. Under these circumstances the field-aligned velocities of the particle streams will mainly be in the $\pm x$ -direction. These velocities are shown in the upper figure in the Earth's (neutral line) rest frame. Subscripts 1 and 2 refer to quantities north and south of the current sheet, E and T to locations Earthward and tailward of the neutral line, and I and O to inflow and outflow parameters respectively. The speeds $v_F = E_y/|B_z|$ are the contraction speeds (de Hoffman-Teller speeds) of the field lines away from the neutral line on either side. We shall adopt the convention that all speeds are positive in the directions shown in the figure. Thus v_{FE} , v_{OE1} and v_{OE2} are all positive in the $+x$ (Earthward) direction, whilst v_{I1} and v_{I2} , together with v_{FT} , v_{OT1} and v_{OT2} are all positive in the $-x$

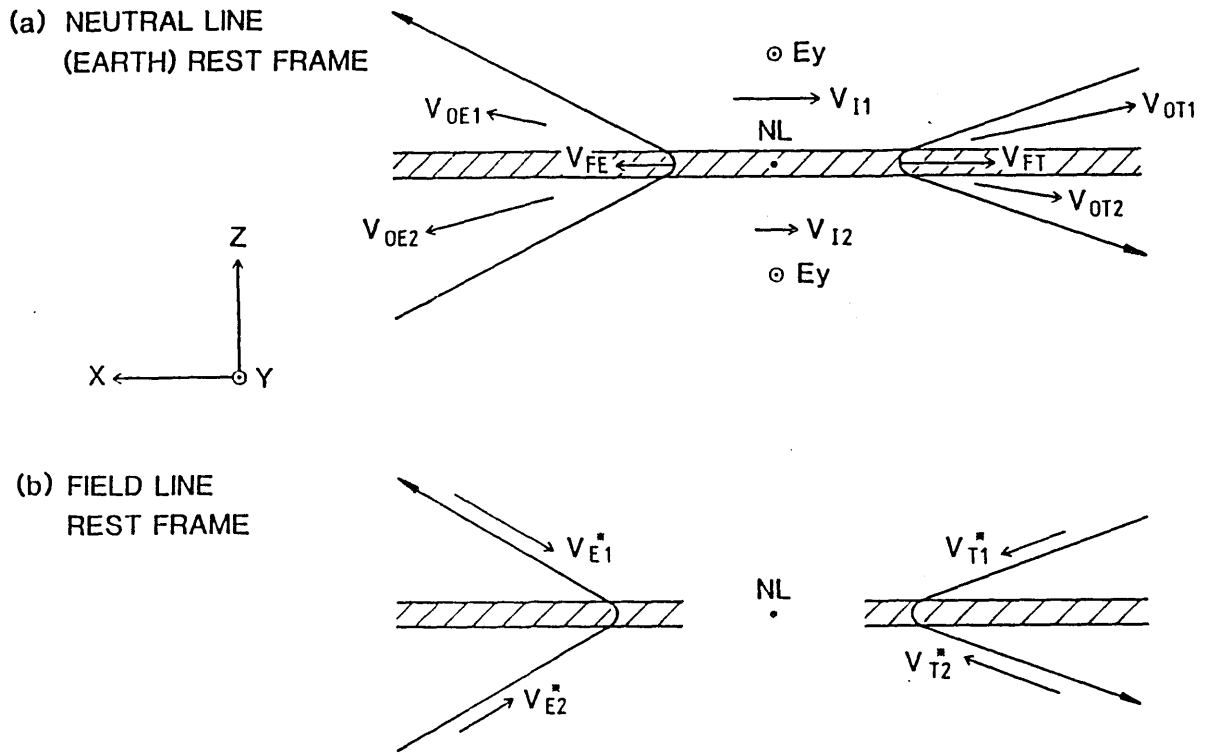


Figure 4.1. Sketch of the field configuration envisaged in this chapter, in which the field lines form sharply bent hairpins about the current sheet (shown hatched) on either side of the neutral line (NL). The upper diagram shows the directions in which the speeds of the inflow plasma v_I , outflow plasma v_o and field lines v_F are taken to be positive in the Earth's (and neutral line) rest frame. The coordinate system employed is as shown. The lower diagram shows the inflows in the field line rest frames on either side of the neutral line obtained by moving along the current sheet, away from the neutral line, with speed v_F . In this frame the plasma inflows are strictly field aligned, and the outflow plasma emerges from the opposite side of the current sheet with the same field aligned speed (not shown).

(tailward) direction. These conventions all accord with the expected signs of these quantities in the tail application. As indicated by the lengths of the arrows in Figure 4.1 we will also assume for definiteness in discussion that $v_{I1} > v_{I2}$ and $n_1 > n_2$, the expected situation corresponding to the dawn side of the tail for IMF $B_y > 0$ and to the dusk side for IMF $B_y < 0$. The formulae given, however, are completely general.

The lower half of the figure shows the situation in the field line rest frames (de Hoffmann-Teller frames) on either side of the neutral line, obtained by moving away from the neutral line on either side with the speeds $v_F = E_y/|B_z|$. Since the electric field is transformed to zero in this frame, the particles experience no $\mathbf{E} \times \mathbf{B}$ drift, so that they simply move into and out of the current layer by drift along the field at the speeds indicated. In addition, the particles experience no change of speed in their interaction with the current sheet in this frame, so that by the above assumptions they emerge from the other side of the sheet as field-aligned beams of unchanged speed and density (not shown). The equilibrium condition is consequently simple to consider in this frame. Combining together the inflow and outflow distributions on either side of the current sheet we have the following equilibrium conditions (from equation 4.13a) for the regions Earthward and tailward of the neutral line respectively

$$m_i (n_1 v_{E1}^{*2} + n_2 v_{E2}^{*2}) = B^2/\mu_0 \quad (14a)$$

$$m_i (n_1 v_{T1}^{*2} + n_2 v_{T2}^{*2}) = B^2/\mu_0 \quad (14b)$$

where the electron terms have been neglected. The starred inflow beam speeds in the field line rest frame may now be related to the given inflow speeds in the Earths' frame by the transformations

$$v_{E1}^* = v_{FE} + v_{I1} \quad v_{E2}^* = v_{FE} + v_{I2} \quad (4.15a,b)$$

$$v_{T1}^* = v_{FT} - v_{I1} \quad v_{T2}^* = v_{FT} - v_{I2} \quad (4.15c,d)$$

where we have assumed $|B_x| \gg |B_z|$ outside the current sheet such that these flows are essentially in the $\pm x$ -direction as previously stated. Substitution of these expressions into (4.14a,b) then yields quadratic equations for v_{FE} and v_{FT} with solutions

$$v_{FE} = R - v_{IM} \quad v_{FT} = R + v_{IM} \quad (4.16a,b)$$

where

$$R = \left(\frac{B^2}{\mu_0 m_i (n_1 + n_2)} - \frac{n_1 n_2 (v_{I1} - v_{I2})^2}{(n_1 + n_2)^2} \right)^{1/2} \quad (4.17)$$

and v_{IM} is the mean of the inflow speeds, weighted according to the beam densities

$$v_{IM} = (n_1 v_{I1} + n_2 v_{I2}) / (n_1 + n_2) \quad (4.18)$$

Note that real solutions exist only if the flow shear

$$\Delta v_I = v_{I1} - v_{I2} \quad (4.19)$$

across the inflows is sufficiently small, i.e. if

$$|\Delta v_I| < \sqrt{(V_{A1}^2 + V_{A2}^2)} \quad (4.20)$$

where

$$V_{A1} = B / \sqrt{(\mu_0 m_i n_1)} \quad V_{A2} = B / \sqrt{(\mu_0 m_i n_2)}$$

are the Alfvén speeds in the northern and southern lobes respectively. For very large flow shears such that equation (4.20) does not hold, no frame can be found in which the stress balance equations (4.16a,b) can be satisfied, and consequently no one-dimensional equilibria of the type considered here can exist. The only simple solution to the problem is then to take $B_z = 0$, i.e. a neutral sheet with no flux threading across it. However, equation (4.20) should be well satisfied in the tail problem at all times, since lobe plasma flow speeds are generally small compared with lobe Alfvén speeds.

In addition, for a steady state to be possible, v_{FE} must be positive, i.e. reconnected field lines on the Earthward side of the neutral line must move Earthwards. For sufficiently strong down-tail lobe plasma flow, however, these field lines will have to move tailwards with the flow in order to achieve stress balance, implying tailward motion of the neutral line and time dependence, as

described in Chapter 2. From equation (4.16a) the required steady state condition is

$$n_1 v_{I1}^2 + n_2 v_{I2}^2 < B^2/\mu_0 m_i \quad . \quad (4.21)$$

When equality holds the stress balance condition (4.14a) is satisfied in the Earth's frame.

We now consider the properties of the outflow beams and their spatial structure relative to the location of the neutral line. Using the result that the beam speeds remain unchanged in the field line rest frame we have, after transforming back into the Earth's frame

$$v_{OE1} = 2v_{FE} + v_{I2} \quad v_{OE2} = 2v_{FE} + v_{I1} \quad (22a,b)$$

$$v_{OT1} = 2v_{FT} - v_{I2} \quad v_{OT2} = 2v_{FT} - v_{I1} \quad (22c,d)$$

and then from equations (4.16a,b) we have

$$v_{OE1} = 2R - v_{IM} - n_1 \Delta v_I / (n_1 + n_2) \quad (4.23a)$$

$$v_{OE2} = 2R - v_{IM} + n_2 \Delta v_I / (n_1 + n_2) \quad (4.23b)$$

$$v_{OT1} = 2R + v_{IM} + n_1 \Delta v_I / (n_1 + n_2) \quad (4.23c)$$

$$v_{OT2} = 2R + v_{IM} - n_2 \Delta v_I / (n_1 + n_2) \quad (4.23d)$$

where R is given by equation (4.17), v_{IM} by (4.18) and Δv_I by (4.19). With the asymmetries shown in Figure 1 (i.e. $\Delta v_I > 0$ and $n_1 > n_2$), and assuming equation (4.21) holds, we then have $v_{OT1} > v_{OE2} > v_{OT2} > v_{OE1}$. Note that Earthward of the neutral line the outflow (plasma sheet) plasma is faster on the southern side of the current sheet than on the northern side in this case (i.e. $v_{OE2} > v_{OE1}$), opposite to the asymmetry in the tail lobes, while tailward of the neutral line the outflow is faster on the northern side than on the southern (i.e. $v_{OT1} > v_{OT2}$), the same sense as the asymmetry in the tail lobes. The shear between the two outflow beams across the current sheet is, of course, just Δv_I

(see equations 23a-d), as is obvious from the consideration of the situation in the field line rest frame.

Turning finally to the spatial structure of the outflow beams, we note that for steady reconnection these form wedges adjacent to the current sheet whose apices meet near the neutral line, since the outer boundary of the wedges is defined by the limiting ion trajectories which originate in the latter's vicinity. The angle of the reconnected field lines to the current sheet is given by

$$\theta = |B_z|/B = E_y/v_F B \quad (4.24)$$

where we have again assumed that outside the current sheet B_z is small compared with B . Equation (4.24) shows that this approximation will be valid provided that the reconnection rate E_y is not too large. Note that E_y remains a free parameter in our analysis. With the same approximations the angle to the current sheet of the boundary (the trajectories) of the outflow particles with field-aligned speed v_o is given by (see e.g. Hill, 1975; Cowley, 1984)

$$\phi \approx (1 - v_F/v_o)\theta \quad (4.25)$$

Note that the faster the speed of the outflow plasma, the larger the wedge angle ϕ , approaching θ when $v_o \rightarrow \infty$ (i.e. the particle boundary then coincides with the separatrix of the X-type field configuration). The minimum plasma outflow speed is v_F , when $\phi \rightarrow 0$. Thus in the present problem the outflow beam (the plasma sheet) will be thicker on the side of the current sheet on which the outflow beam is fastest.

In Figure 4.2 we illustrate these results by showing the field and plasma sheet configuration for the case $v_{I1} = 0.5 V_{A1}$, $v_{I2} = 0$ and $n_2 = 0.25 n_1$ (and hence $V_{A2} = 2V_{A1}$). The specific wedge angles shown are for the reconnection rate $E_y/B = 0.2V_{A1}$, but the configuration for any other E_y can be found simply by scaling the vertical axis relative to the horizontal. Thus, for example, for half this reconnection rate the vertical scale should be halved relative to the horizontal. In this diagram the horizontal solid line represents the current sheet, the arrowed solid lines the field separatrices mapping to the neutral line, and the hatched region bounded by the dashed lines shows the region occupied by the accelerated ions (the plasma sheet). The inflow and outflow speeds are also shown. Since in this case $v_{I2} = 0$, the plasma outflow speeds north of the

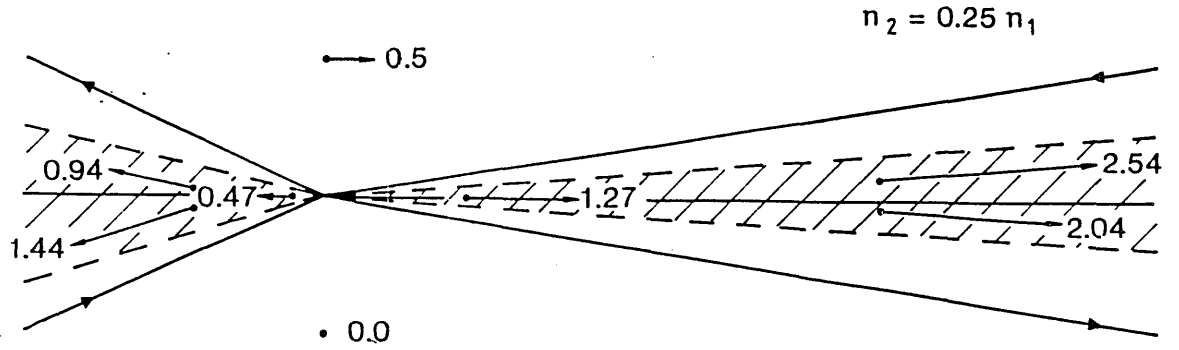


Figure 4.2. Plasma sheet and reconnected field configuration for the case $v_{I1} = 0.5 V_{A1}$, $v_{I2} = 0$, $n_2 = 0.25n_1$, and $E_y/B = 0.2 V_{A1}$. The horizontal line represents the central current sheet, the arrowed solid lines the field separatrixes mapping to the neutral line, and the hatched region bounded by the dashed lines the plasma sheet containing accelerated ions. The numbers indicate speeds in units of V_{A1} , those on the central axis being the field line speeds, whilst those off the axis give the inflow and outflow beam speeds in the various regions. The Earth is to the left.

current sheet are just twice the respective field line speeds, and the outflow wedge occupies just half of the wedge of reconnected field lines (equations 4.22 and 4.25). South of the current sheet, however, the outflow speed exceeds that in the north and occupies more than half the field wedge on the Earthward side of the neutral line, while being slower than that in the north and occupying less than half the field wedge tailward of the neutral line. For a given sign of IMF B_y the sense of these North-South asymmetries applies only to one flank of the tail, and are expected to be reversed on the other, as previously explained. However, the general asymmetry in wedge thickness and outflow speeds between the regions Earthward and tailward of the neutral line will be a common feature, due to the mean tailward streaming of the inflow plasma.

4. Summary

Previous analyses of the structure and properties of accelerated plasma populations in the more 'distant' geomagnetic tail, where the 1-D approximation is appropriate, have, for simplicity, assumed symmetry of the inflow plasma conditions on either side of the current sheet. Here we have considered the more general equilibrium conditions applicable to asymmetrical inflow and have expressed the results in a form which does not make artificial distinctions between stress balance due to anisotropic plasma pressure and that due to flow through the current sheet. We have then applied this theory to the tail problem, where the inflow plasma may be taken to form cold beams of differing density and down-tail field-aligned speed. Significant lobe plasma asymmetries have recently been shown to occur due to effects associated with IMF B_y . The lobe plasma asymmetry will in general lead to asymmetries in the accelerated plasma sheet populations on either side of the current sheet, both in terms of plasma speed and layer thickness. Assuming that all particles incident on the current sheet are transmitted through it, as seems a reasonable first approximation, on the Earthward side of the neutral line the accelerated particles will be faster, and the layer thicker, on the side of the current sheet opposite to the lobe which contains the faster downtail flow. Tailward of the neutral line, however, the outflows are faster and thicker on the same side of the current sheet as the latter lobe. It has also been shown that if the flow shear across the inflows becomes too large, one-dimensional current sheet equilibria cease to exist. This condition, however, is most unlikely to occur in the tail problem.

CHAPTER 5.
ENERGETIC IONS IN THE LOBES OF THE DISTANT
MAGNETOTAIL

1. Introduction

As explained in the introduction to this thesis, results from the ISEE-3 exploration of the nightside region of the Earth's magnetosphere during 1982-3 show that the distant tail has a coherent structure, similar to that in the near-Earth tail, out to at least 240 R_E from the Earth. This structure consists of two lobes of strong magnetic field, with direction pointing towards the Earth in the northern lobe, and away from the Earth in the southern lobe. These two regions are separated by the equatorial plasma sheet consisting of fast streaming plasma where, along with the associated boundary layers, the highest energetic ion intensities ($I \geq 10^3$ (s cm² sr keV)⁻¹ for ions of 35 - 56 keV) found in the deep tail are observed (Richardson and Cowley, 1987). This central region has been the subject of the previous chapters of this thesis, as well as numerous published papers (e.g. Hones et al., 1984, Zwickl et al., 1984, Slavin et al., 1985, Scholer et al., 1986, Richardson et al., 1987), and the CDAW-8 data analysis workshop, and thus has received a high level of attention and interest during the last 4 or 5 years. In contrast, however, the tail lobes remain a relatively neglected area of study in both the near-Earth and deep-tail data sets, largely due to the less exotic and less varied nature of phenomena observed in these regions. The energetic ion intensities within the lobes are much reduced compared to the plasma sheet ($I \leq 10^0$ (s cm² sr keV)⁻¹), whilst their pitch angle distribution has a characteristic "pancake"-like nature, in which the distribution is peaked closely perpendicular to the magnetic field direction, compared to plasma sheet ions which show a clear streaming in the tailward direction in the deep tail (Cowley et al., 1984, Daly et al., 1984). In addition, the energetic ions in the magnetosheath adjacent to the tail lobes are also observed to stream tailward with intensities comparable to those in the plasma sheet, although varying on time scales of a few minutes. The deep tail lobes are therefore regions of depressed energetic ion intensity compared to both the adjacent plasma sheet and magnetosheath regions, and also have a very different form of pitch angle distribution.

The aim of this chapter is to present a simple explanation of the properties of the energetic ion populations in the deep tail lobes, deduced from the properties of the source distribution for these ions, and their subsequent motion into and within the lobes. The energetic ion data used in this chapter again come from the EPAS instrument on ISEE-3, and in the next section we shall consider some further aspects of this instrument, specifically those relevant to the lobe

observations. In section 5.3 we shall briefly consider some aspects of the observed energetic ion characteristics in the deep tail lobes, using the EPAS data in conjunction with data from other instruments on the spacecraft.

In this chapter we shall show that the lobe ion population most likely originates in the magnetosheath, and we shall assume that the ions gain entry to the lobes across an open tail magnetopause boundary. The energetic ion distribution function in the lobe then depends on the characteristics of the distribution of the magnetosheath source, the nature of the magnetopause boundary between the lobe and the source, the physics of particle transmission across this boundary, as well as the subsequent motion of the ions within the lobe. The following section (5.4) therefore discusses the properties of the distribution of energetic ions in the magnetosheath, which is shown to be the source of the lobe ions, and the interaction of the particles with the tail magnetopause, whilst section (5.5) deals with the particle motion in a simple model lobe, in which the magnetic field is assumed to be constant in both strength and direction. The pitch angle distributions produced by the model are also discussed in the latter section, and their dependence on both position in the lobe and properties of the magnetosheath are studied. Finally, in section (5.6) the model is revised to include some field strength increase in the near Earth tail ($x_{gse} \leq -100 R_E$) in order to make the model slightly more realistic. It is shown that the results do not differ qualitatively in form from the simple model, which may therefore be considered adequate to explain the main observed characteristics of the lobe energetic ions.

2. Pitch Angle Distributions in the Deep Tail

In chapter 3 data from the EPAS instrument on ISEE-3 was used to study some properties of the deep tail plasma sheet, specifically those properties which were considered theoretically in the previous chapter. Some of the properties of the instrument were described in that chapter. Since the plasma sheet and boundary layer ions form either Earthward or tailward jetting beams, depending on the relative location of the tail neutral line, and only two look directions of one telescope were explicitly used, as the ratio of tailward to Earthward jetting fluxes only was sufficient for our purposes. We also implicitly used observations of 90° pitch angle particles to remotely sense the motion of the energetic ion boundary layers across the spacecraft location. In this chapter, however, we wish to study the energetic ion distribution in the tail lobes, and

since this is not of a simple beam nature, we wish to make fuller use of the directional properties of the instrument. These will therefore be recapped in this section, and we shall also describe quantitatively how various pitch angle distributions appear in the EPAS data set.

The angular extent of the EPAS data coverage was illustrated in Chapter 3 (Figure 3.1), showing how the counts from each of the three telescopes are binned into 8 azimuthal sectors, thus giving a total of 24 look directions per spacecraft spin period (16 seconds). The magnetic structure of the lobes is such that the field points almost directly towards the Earth in the northern lobe, and almost directly away in the southern lobe, and lies closely parallel to the ecliptic plane in both cases (Tsurutani et al., 1987). As explained in Chapter 3, the look directions corresponding to telescope 2 sectors 1 and 5 are therefore those which look most closely along the field lines, and consequently detect the most field aligned particles (those with pitch angles approaching 14° and 166° , the limits of the EPAS field of view for this case). Sectors 3 and 7 of all the telescopes, however, look closely perpendicular to the field direction and therefore detect those particles which have pitch angles close to 90° . For the particular field configuration that is found in the lobes the widest range of pitch angle that is sampled by a single telescope is collected by telescope 2, and we shall consequently concentrate on data from this telescope when referring to the lobes for the rest of this chapter.

Figure 5.1 illustrates the forms of several different types of distribution function in three different formats. The first column shows contours of constant f in velocity space, when the magnetic field is considered to be pointing in the negative x -direction, as is the case in the south lobe of the geomagnetic tail. These plots have been rotated so that the positive x -direction (and hence positive V_x -direction) points towards the bottom of the page. The direction of the sun is then towards the top of the page, which is in common with the convention that has been employed for presentation of the EPAS data, as will be discussed shortly. The second column re-interprets this information in terms of f versus particle pitch angle plots at a particular particle energy, where 0° represents particles travelling along the field in the negative x -direction in this case, 90° those moving perpendicularly to the field, and 180° those moving back along the field line in the positive x -direction. This form of presentation is the most convenient for the purposes of modelling the lobe energetic ion data, and will be used extensively in later sections. The final

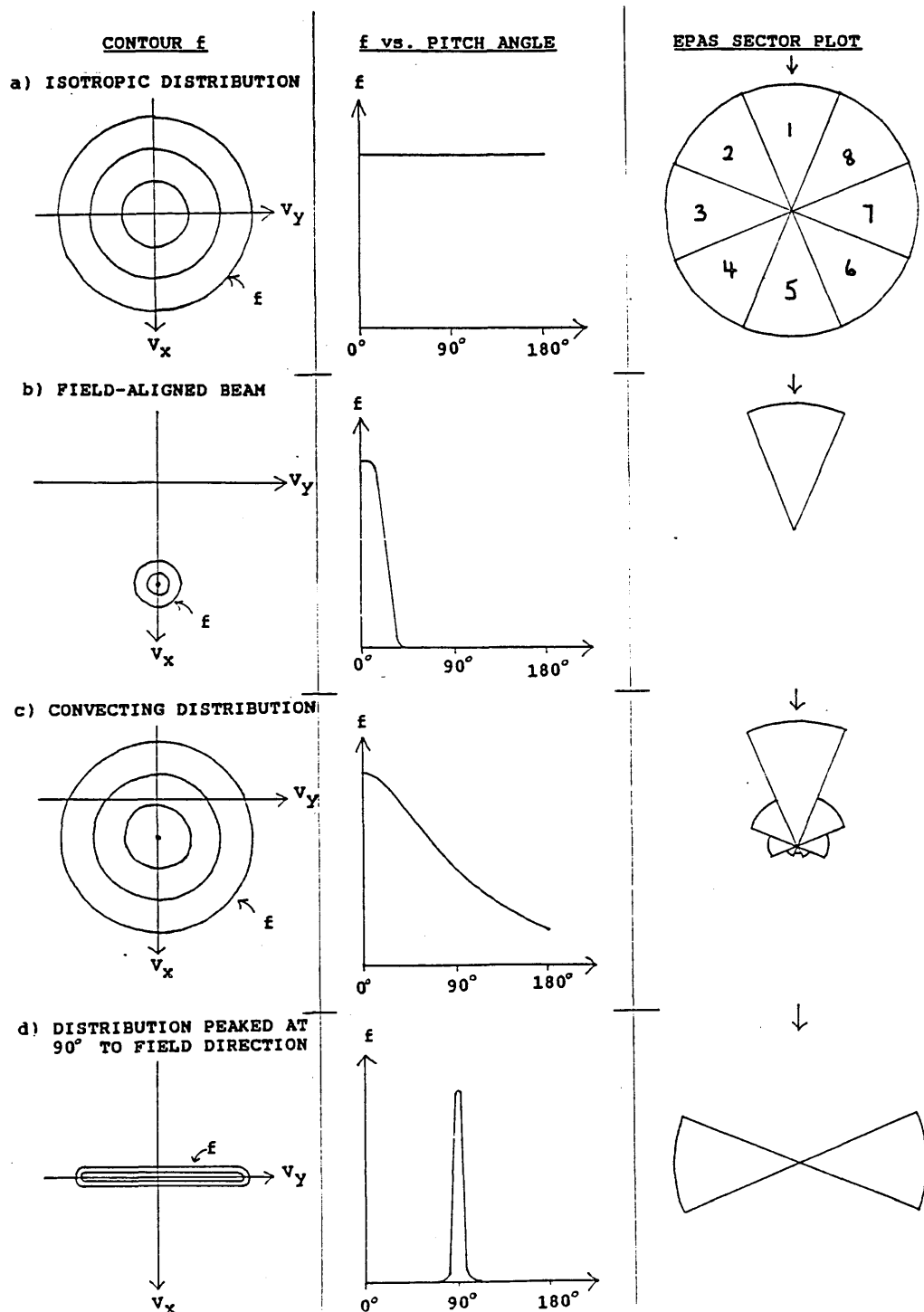


Figure 5.1 Three methods of representing the distribution function of energetic ions. The first column of the figure shows the distribution in two dimensional velocity space, in which the positive V_x -direction is aligned with the field direction, which is taken to point down the page. The second column shows the distribution function plotted against particle pitch angle, which is the method most convenient for plotting modelled results, and the third column indicates qualitatively how the distribution is expected to appear in Telescope 2 of the EPAS instrument (looking closest to the ecliptic). The field direction also points down the page in this column, and the sun is taken to be at the top of the page, the situation expected in the south lobe of the tail. Four types of distribution function are shown: a) an isotropic distribution; b) a field aligned beam; c) a convecting distribution and d) a distribution peaked closely perpendicular to the field direction.

column sketches the distributions in terms of how they would appear in a sector plot of one spin period of EPAS telescope 2 (looking closest to the ecliptic) data. Note that these plots are drawn to represent the particle count in each of the telescope 2 look directions, such that the top sector in each plot represents the (most) sunward look direction. We denote this sector to be Sector 1, and label the others 2 to 8 in an anti-clockwise direction from this sector. The size of each sector is then drawn to be proportional to the number of particles entering the telescope from that look direction, such that, for instance, a large Sector 1 (sunward look direction) indicates an abundance of particles moving in an antisunward (positive x) direction. This point is illustrated further below, when we discuss the individual pitch angle distributions shown in this figure. The small arrow in each of these sector plots represents the component of the magnetic field in the GSE x - y plane relative to these look directions (note though that in the case of the lobe the field is largely confined to this plane, such that this arrow represents the actual field direction).

The first group of plots represents an isotropic distribution. This appears as a set of concentric circles in the contour f representation, and as a horizontal line in the f versus pitch angle plot, since there is no variation of f with pitch angle at a fixed energy in this case. For this reason, there is also no variation of f with look direction, and the EPAS plot is therefore a full circle. The second group represents a closely field aligned beam, where all particles have only a small component of velocity transverse to the field direction, and thus have small pitch angles only (although these must be greater than 14° in order to be detected by EPAS). This therefore appears as a single sector in the look direction opposed to the magnetic field direction. No particles are detected in the other look directions. The third group represent a convecting distribution, in which the distribution is isotropic in a frame convecting slowly (cf. the particle velocity) along the field in the positive x -direction with respect to the rest frame (i.e. an antisunward convecting distribution in the lobe). Those particles moving along the field with closely zero pitch angle have higher values of f than those with higher pitch angles, as illustrated in the f versus pitch angle plot, and this appears in the EPAS sector plot as a large sector 1, looking back down the field, with smaller sectors on either side, the smallest sector being that with the look direction along the direction of convection, Sector 5. The final group of plots, which will prove to be most relevant in this case, are for a distribution which is peaked closely perpendicular to the field

direction. These particles have very small velocities along the field lines, and appear as a sharp peak in f about the 90° pitch angle. Such a distribution appears as 2 large sectors in the look directions perpendicular to the field (sectors 3 and 7), with other sectors having small or zero counts. The principles described above can therefore be used to infer the type of distribution present in the lobes from the EPAS data, which we shall look at in more detail in the next section.

3. ISEE-3 Observations of Energetic Ions in the Distant Tail Lobes.

In this section the main characteristics of the energetic ($E \geq 35$ keV) ion distributions observed in the tail lobes using the EPAS instrument on ISEE-3 will be discussed. In order to assist in the interpretation of the ion data, simultaneous observations of the lobe magnetic field by the Jet Propulsion Laboratory's vector helium magnetometer (Frandsen et al., 1978), and the thermal plasma electrons by the Los Alamos electron experiment (Bame et al., 1978) are also employed, as in chapter 3.

Three intervals of data for periods when ISEE-3 was located in, or making a traversal of one of the deep tail lobes will be presented in this section. The first of these is a period where the spacecraft is located in the lobe for a period of several hours. This is somewhat unusual in the data set, but readily demonstrates the prevalent conditions in the lobe. The next interval covers a traversal of the spacecraft across the tail magnetopause. This interval has previously been discussed, with regard to the electron plasma data, by Gosling et al. (1984), and, for current purposes, will be used to show the variation of the ion distributions with distance from the magnetopause. The final interval of data is taken from a period when the energetic ion fluxes in the solar wind are dominated by solar flare particles, and are enhanced by several orders of magnitude above average solar wind fluxes. Under these circumstances, the lobe ion distribution is dramatically altered, and any model attempting to explain the observations in the lobe should be able to account for the differences observed during these solar particle events, as well as the ion characteristics under more usual conditions.

The first period of interest occurred on 23rd January 1983, when ISEE-3 was located some 200 R_E downstream from the Earth. The magnetic field measurements for the period 1000 UT to 1500 UT on this day are shown in

Figure 5.2. The top panel of this figure represents the magnetic field strength observed by ISEE-3 during the day, whilst the lower panels indicate the direction of the magnetic field vector. The angle θ measures the inclination of the field out of the ecliptic plane ($\theta = 90^\circ$ represents a field pointing directly northwards out of the plane), whilst ϕ represents the azimuthal direction of the field with $\phi = 0^\circ$ representing a field pointing towards the Earth in the deep tail context. It can be seen from the figure that for the whole of this period the magnetic field vector lies closely in the plane of the ecliptic ($\theta \approx 0^\circ$) and points almost directly away from the Earth ($\phi \approx 180^\circ$). The field strength is also quite steady at a value of $|B| \approx 9$ nT. These observations are consistent with the spacecraft being located within the southern lobe of the geomagnetic tail during this period (cf. Chapter 3). The omnidirectional energetic ion fluxes for the first two energy channels of the EPAS instrument, averaged over 4 spacecraft spin periods (i.e. 64 seconds), for the period 1000-1500 UT are shown in Figure 5.3. The intensities observed during this period are generally small (cf. typical plasma sheet fluxes $\approx 10^3$ (s cm² sr keV)⁻¹), although still well above the instrument background ($I \ll 10^{-2}$ (s cm² sr keV)⁻¹), and are approximately constant, especially during the latter part of this period. The directional variation of these fluxes is shown in Figure 5.4, showing the sector plots in each of the three EPAS telescopes for the lowest energy channel (35-56 keV). The plots cover the period from about 1300 UT until about 1343 UT (the period marked by the horizontal bar in Figure 5.3), and are averaged over 20 spin periods of 16 seconds each. We re-emphasize that the size of the sectors represents the count rate in that telescope look direction, as explained above, and the small arrows in the main panel of the plot indicate the direction of the magnetic field in the GSE x-y plane (to which telescope 2 has the closest look direction), with the direction of the Earth at the top of the figure (i.e. these arrows represent a field pointing away from the Earth as shown above). Similarly the arrows at the bottom of the panel represent the direction of the field in the x-z plane, indicating the degree of inclination of the field out of the ecliptic, which is small in this case, as expected for the lobe field. With this particular field configuration the plot for telescope 2 represents the widest range of sampled pitch angle, since it looks most closely along the field direction in sectors 1 and 5 (pitch angles up to 166° and down to 14° respectively in this case) and in directions perpendicular to the field direction in telescopes 3 and 7 (pitch angles 90°). Since the other two telescopes look further out of the ecliptic plane, and therefore at a greater angle to the field

JANUARY 23 1983 DAY=023 UT 10:00 00

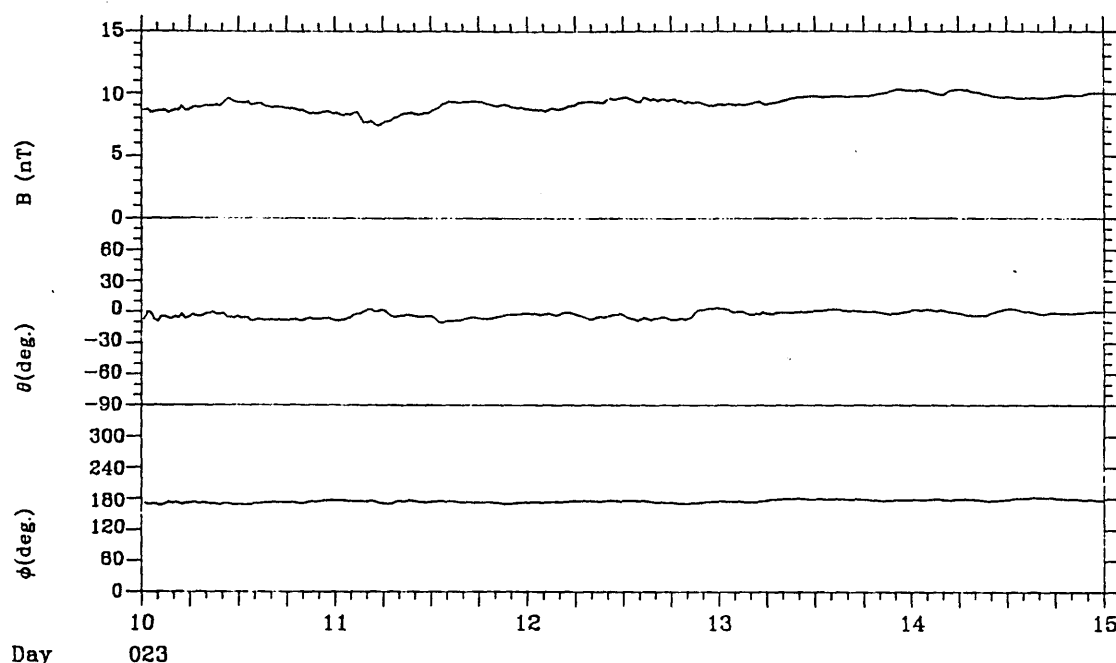


Figure 5.2 Magnetic field data for a period of 5 hours between 1000 and 1500 UT on the 23rd January 1983. The top panel shows the strength of the magnetic field, whilst the lower two panels indicate the direction of the field. The angle θ represents the inclination of the field out of the ecliptic plane, such that $\theta = 90^\circ$ represents a field pointing northwards, directly out of the ecliptic. The angle ϕ represents the azimuthal angle of the field in the ecliptic plane, where $\phi = 0^\circ$ represents a field pointing towards the Earth in the context of the deep tail. The period is unusual in the tail data set in that each of the field parameters is approximately constant throughout this extended period. The field strength is strong at 9 - 10 nT, whilst $\theta \approx 0^\circ$, $\phi \approx 180^\circ$, shows the field is confined to the ecliptic plane and points directly away from the Earth. These field parameters are consistent with those expected for a spacecraft location in the south lobe of the geomagnetic tail throughout this period.

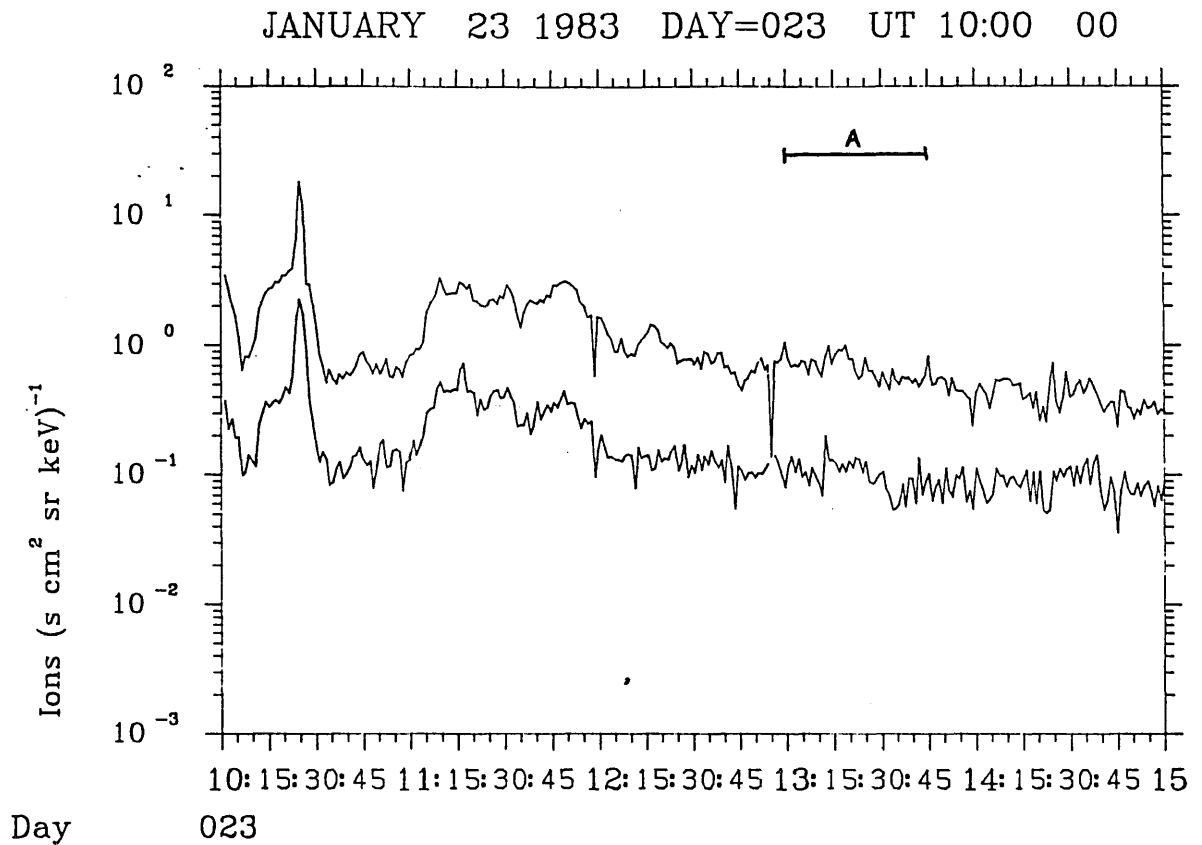


Figure 5.3 The direction-averaged energetic ion fluxes from the lowest two energy channels (35 - 56 and 56 - 91 keV) of the EPAS for the period 1000-1500 UT on the 23rd January 1983, at 64 second resolution. As indicated by the previous figure, the spacecraft is located in the south lobe during the whole of this period. The ion intensities observed during this period are low compared to the plasma sheet fluxes observed in Chapter 3, and show little fluctuation, especially during the latter part of the interval. This indicates that the spacecraft is located in the lobe proper, and not in the plasma sheet boundary layer. The horizontal bar, marked A, at the top of the figure indicates the period of approximately 43 minutes for which the directional properties of the ions are shown in the next figure.

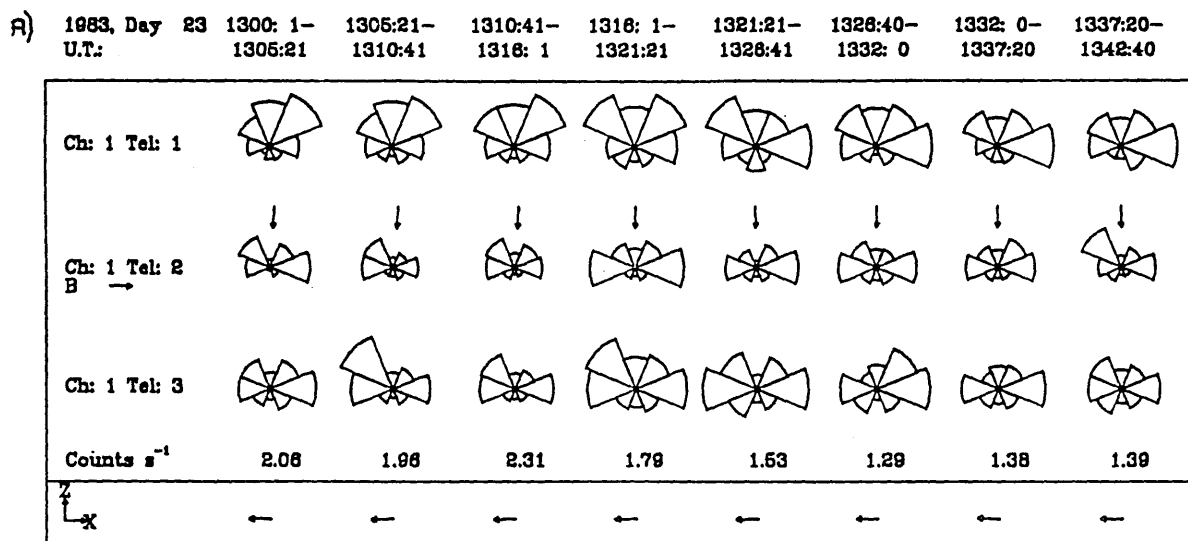


Figure 5.4 EPAS sector plots for the period 1300 -1343 UT on 23rd January 1983 (the period marked by the horizontal bar in the previous figure). The figure represents each of the look directions of each of the three telescopes, for the lowest (35 -56 keV) energy channel, drawn such that sector 1, representing the sunward look direction, is at the top of each plot. The size of each sector represents the relative count rate in that sector, and the number at the bottom represents the maximum count rate recorded during each period. The small black arrows represent the direction of the magnetic field in the x-y (ecliptic) plane in the main body of the figure and in the x-z plane at the bottom. In this case the field points directly away from the sun and is confined to the ecliptic plane. In this field configuration telescope 2 (the central set of plots) samples the widest range of ion pitch angle. This telescope shows high counts in the sectors which have look directions closely perpendicular to the field direction (sectors 3 and 7), indicating that the distribution function is peaked at pitch angles close to 90°. The sunward look directions (sectors 1, 2, 8) show higher counts than those looking antisunward (sectors 4, 5, 6), indicating that there is also a net antisunward flow in the lobe energetic ion distribution. These plots show typical "pancake" like distributions.

direction they detect a smaller range of pitch angle than telescope 2 ($\geq 44^\circ$ and $\leq 136^\circ$ for telescope 1; $\geq 29^\circ$ and $\leq 151^\circ$ for telescope 3). Any variation in flux with pitch angle is consequently less marked in these telescopes (especially telescope 1) than in telescope 2, and we shall therefore be concentrating on the central set of plots, which are those from telescope 2. These plots are typical examples of the type that have led the lobe energetic ion distribution to be labelled a "pancake" distribution – they show consistently higher count rates in sectors 3 and 7, the telescope look directions sampling the particles with pitch angles closely perpendicular to the field direction, than in sectors 1 and 5, which see the more field aligned particles. As discussed in the last section, this indicates that the pitch angle distribution in the lobes at this time has a peak at pitch angles around 90° , and falls off at both higher and lower pitch angles. It should be noted also that the sectors representing the more sunward-looking directions (sectors 1,2,8 at the top of each plot) show consistently higher count rates than the corresponding antisunward-looking directions (sectors 4,5,6 at the bottom of each plot). This indicates a net anti-sunward streaming in the lobe energetic ion distribution, such that the average value of $f(v_{\parallel}, v_{\perp})$ for tailward streaming particles must be larger than that for those streaming Earthwards. The fundamental properties of the distribution function are therefore that it is quite highly peaked for those particles which are moving perpendicular to the field direction, whilst maintaining a net antisunward anisotropy in the field-aligned components of the flow.

We shall now move on to study the variations in the distributions as a function of position in the tail. The next period of data presented here has been previously discussed by Gosling et al. (1984). These authors found that the transition in the magnetic field and plasma parameters as the spacecraft crossed the tail magnetopause may be either gradual, indicating a locally "open" magnetopause with the sheath field connecting into the lobe and associated plasma entry from the sheath, or, at other times, abrupt, suggesting a locally "closed" magnetopause with no field connection and no plasma leakage between the sheath and lobe at this location. Note however, that the flux tube in the latter case must be globally open, if not locally so, and thus connects into the sheath at some point downstream from the spacecraft, where plasma from the sheath may enter the lobe. This is illustrated in Figure 5.5, showing the global nature of lobe flux tubes lying close to the magnetopause. In this figure, field lines that lie adjacent to the magnetopause, but do not connect into the

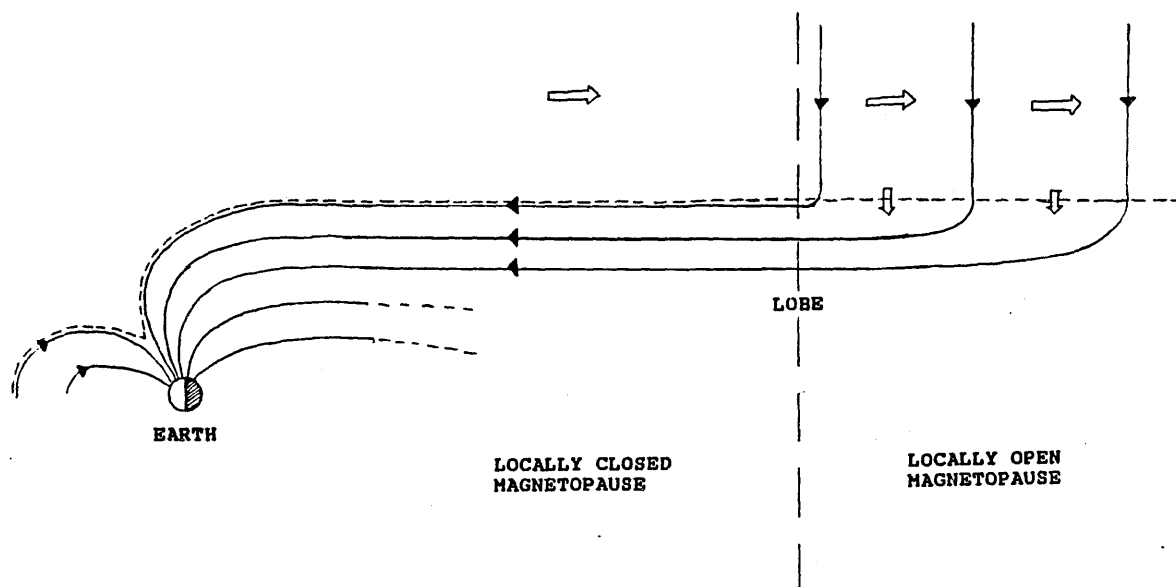


Figure 5.5 Schematic diagram illustrating the field configuration for "closed" and "open" magnetopause boundaries in the deep tail. The solid arrowed lines represent the magnetic field close to the magnetopause, which is represented by the dotted line. The open arrows represent the direction of plasma flow. Field lines which lie adjacent to the magnetopause close to the Earth and have no connection into the magnetosheath form a locally "closed" boundary, but must be "open" on global scale, such that they connect into the magnetosheath at some point further tailwards. At this point the magnetopause is said to be locally "open", and plasma may enter the lobes from the magnetosheath in this region.

magnetosheath close to the Earth, form a locally "closed" magnetopause in this region. However, at greater distances down the tail the same field lines do connect into the IMF, forming a locally "open" magnetopause, allowing plasma entry into the magnetopause at this point. The Gosling et al. (1984) observations suggest that, for the case of an open magnetosphere at least, the magnetosheath is the source of plasma and energetic ions in the lobes, and we shall assume this to be the case for our model. A case of an open magnetopause crossing by ISEE3 discussed by Gosling et al. (1984) is presented for our purposes in Figure 5.6. This covers the period from 0000-0300 UT on the 31st January 1983, when ISEE-3 was located at 218 R_E downtail from the Earth. This figure shows the electron plasma data (the top four panels representing electron density, temperature, and flow speed and azimuth (in the GSE xy plane) and the magnetic field (bottom three panels showing magnitude, ϕ , θ , with the same convention employed in Figure 5.3). The period includes two tail magnetopause crossings; out from the south lobe into the magnetosheath at 0115 UT, and in the opposite direction at 0132 UT. The lobe is identified from the strong, tail aligned field ($|B| \approx 10$ nT, $\phi \approx 180^\circ$, $\theta \approx 0^\circ$) and the low density, high temperature electron plasma parameters, whilst, in comparison, the sheath field is depressed and more variable in direction, and the electron plasma shows an increase in density and a drop in temperature. In addition the tailward flow speed increases to values of $400\text{-}500 \text{ km s}^{-1}$ when the spacecraft is in the magnetosheath. The next figure (Figure 5.7) shows the direction-averaged ion intensities for the 3 lowest energy channels of the EPAS instrument. Note that the energetic ion intensities observed whilst the spacecraft is located in the magnetosheath are considerably higher (by a factor of ≈ 30) than those found in the lobes. The angular distributions of the 35-56 keV ions during this period are shown in Figure 5.8, in the same format as above (although panels B, C, and D are 64 second averages). The letters above each plot relate to the corresponding letter on the omnidirectional ion intensity plot of the previous figure, thus showing the time of each plot relative to the rest of the data.

The first magnetopause crossing, at 0113 UT, is characterised by abrupt changes in both the field and electron plasma parameters. Gosling et al. (1984) concluded that this is due to the spacecraft encountering a locally closed magnetopause, where there is no local field connection between the lobe and the magnetosheath, and no plasma leakage between the two regions at this

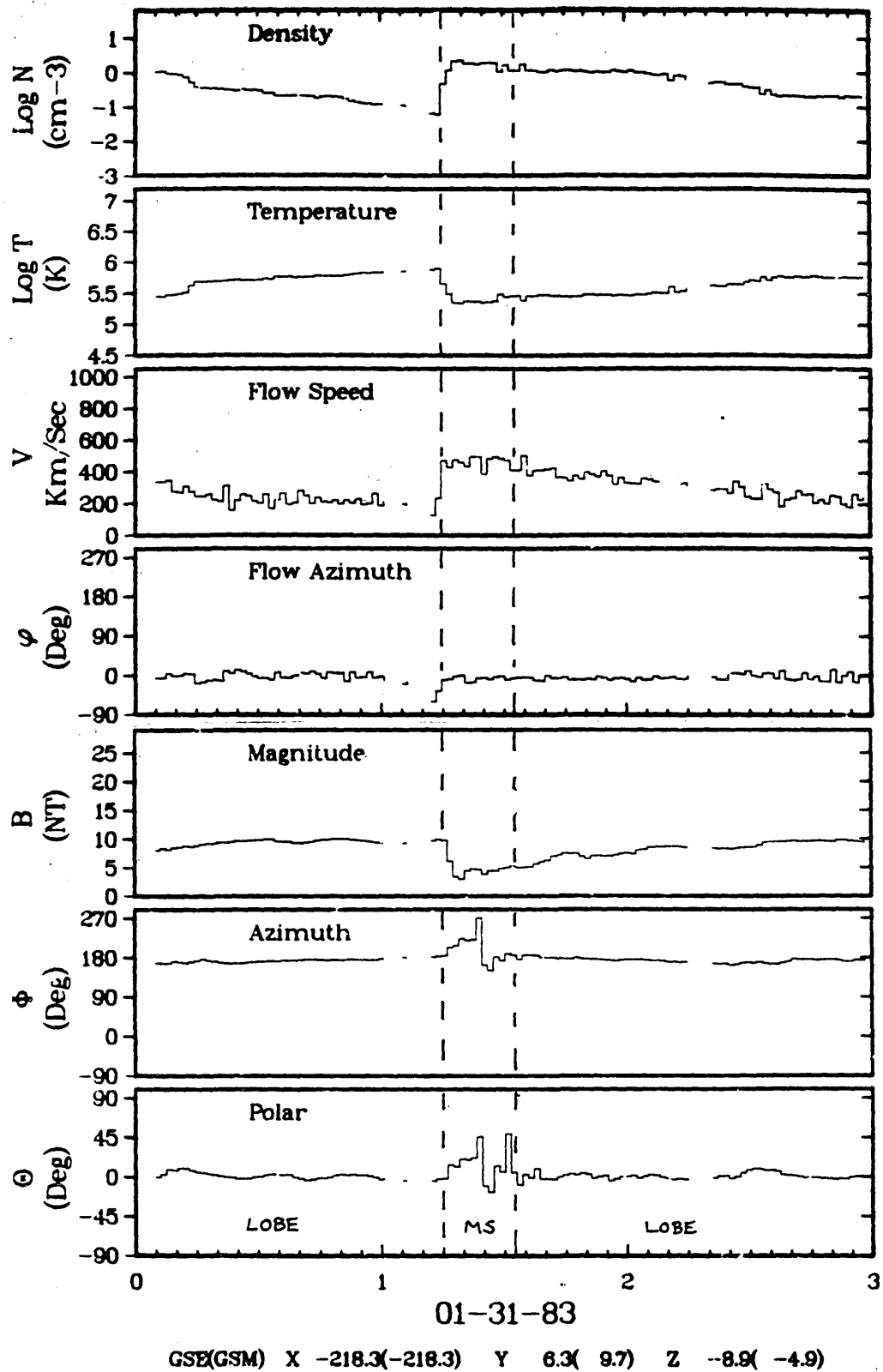


Figure 5.6 Plasma and field parameters on January 31 1983, when the spacecraft is located 218 RE downtail from the Earth. The upper 4 panels show the electron plasma density, temperature, and bulk flow speed and azimuth. the remaining panels show the field parameters, with the same convention employed previously. The spacecraft spends most of this period within the lobe, but makes a brief exit into the magnetosheath (higher density and flow speed, lower temperature, and more variable field parameters) between 0113 and 0133 UT. The first magnetopause crossing shows abrupt changes associated with a "closed" magnetopause, whilst the second crossing shows more gradual changes, consistent with an "open" magnetopause.

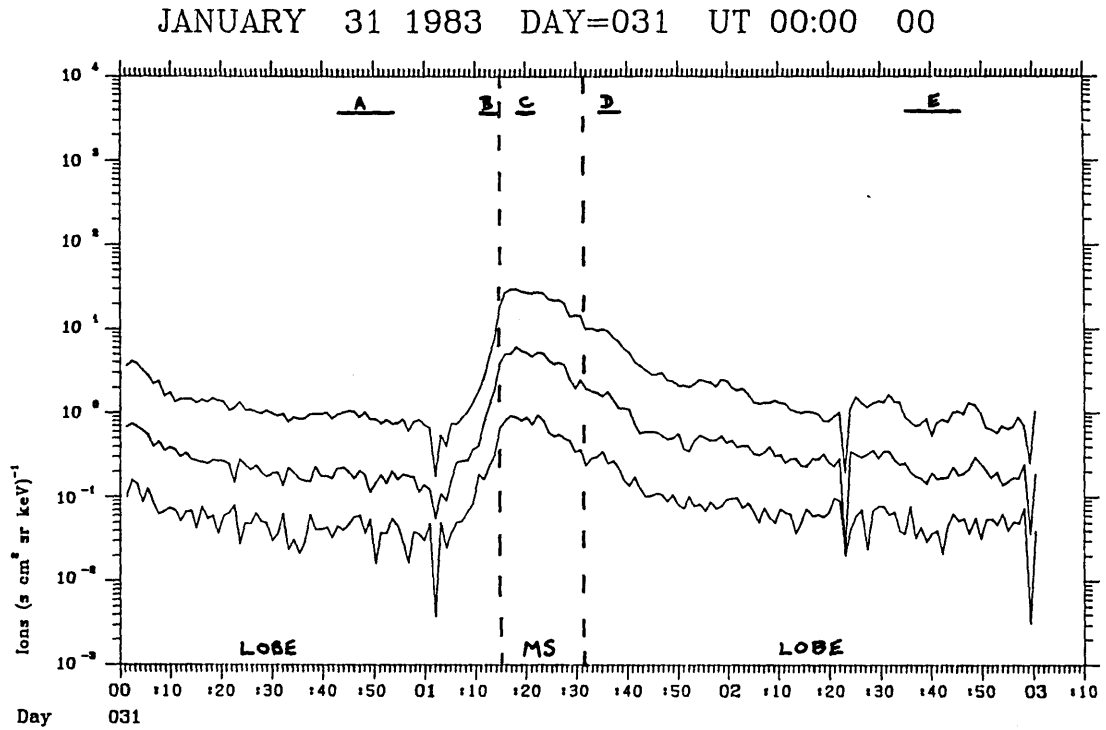


Figure 5.7 Direction averaged energetic ion fluxes from the lowest 3 EPAS energy channels for the same period described in Figure 5.6. The lobes are characterised by low fluxes as observed in the previous case, which rise quite abruptly at the first magnetopause crossing. On re-entry to the lobes the ion fluxes fall more gradually. This is similar to the electron plasma variations for this period. The labelled horizontal bars at the top of the figure refer to the times of the EPAS sector plots shown in the next figure.

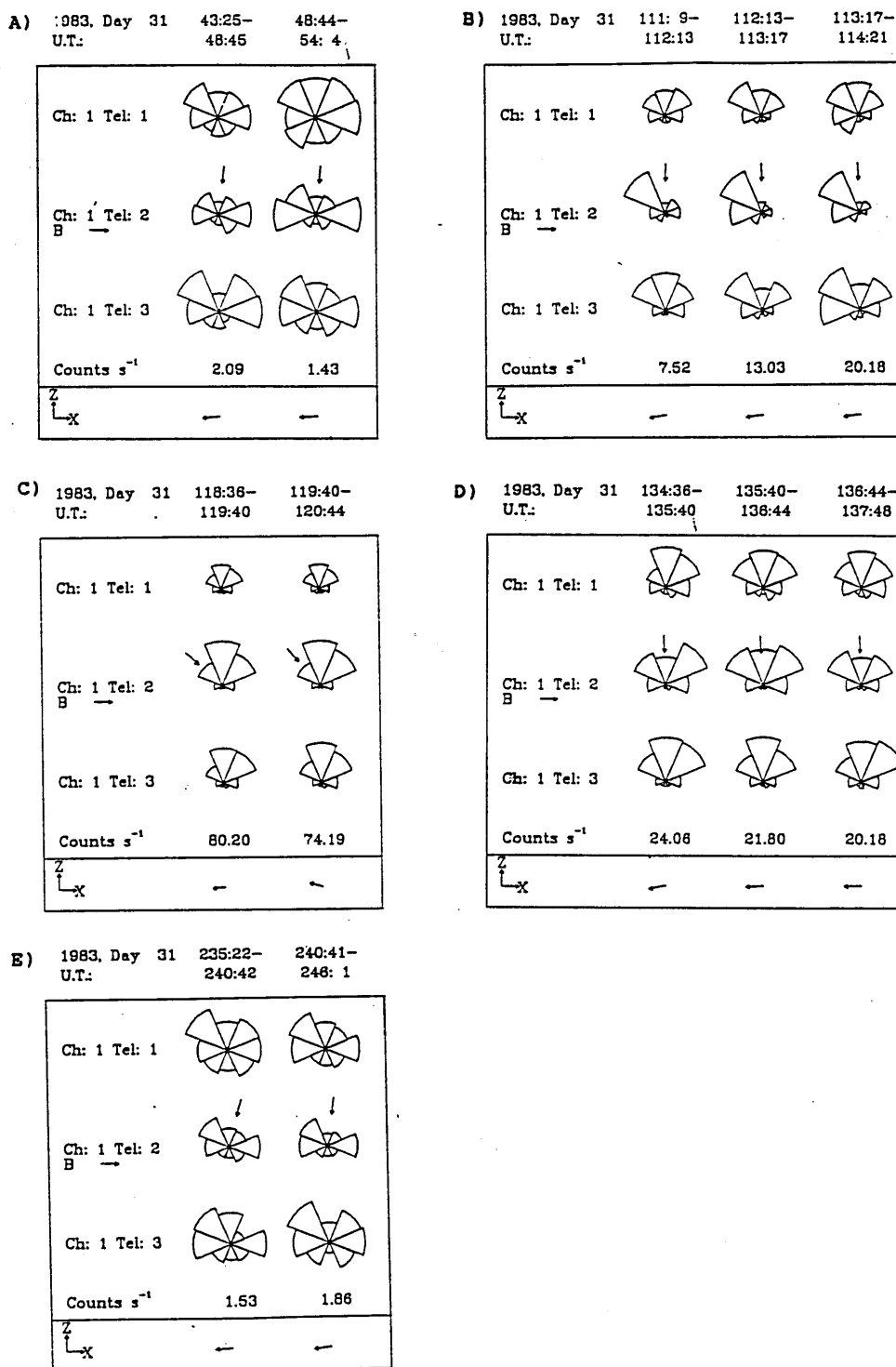


Figure 5.8 EPAS sector plots for the periods marked by the horizontal bars in the last figure, in the same format as employed previously. Panels (A) and (D) are taken from periods when the spacecraft is well away from the magnetopause, and shows the "pancake" distributions described previously. Panel (C) is taken when the spacecraft is located in the magnetosheath, and shows a convecting type distribution (cf. Figure 5.1). The remaining two panels are taken when the spacecraft is in the lobe, but close to the magnetopause. Panel (B), taken just prior to the first crossing shows a significant dusk to dawn anisotropy, consistent with a $\mathbf{B} \times \mathbf{grad} n$ anisotropy associated with a "closed" magnetopause which the ions cannot cross. Panel (D), taken shortly after the second magnetopause crossing shows a distribution which is intermediate between that observed in the magnetosheath and deep in the lobe (panels (C) and (E)), and suggests that sheath ions do have access to the lobes in this case.

point, although both field and plasma must cross the magnetopause at a location further tailwards (cf. Figure 5.5). The direction averaged intensity of the energetic ions begins to rise some 8 or 9 minutes prior to the magnetopause crossing, and during this rise the pancake-like lobe angular distribution with highest counts in sectors 3 and 7 (plot A of Figure 5.8), changes to one showing a significant dusk-to-dawn anisotropy, where the highest counts are observed in sectors 2 and 3 (plot B), which then turns tailward at the magnetopause (highest counts in the sunward look direction, sector 1, plot C). If the magnetopause at this point is indeed closed, then the ions from the sheath region, where the ion intensity is about two orders of magnitude higher than that in the lobe, may penetrate no more than a gyroradius into the lobe before being returned to the sheath by virtue of their gyromotion. A layer of ions of this thickness would therefore be expected to exist just inside the magnetopause boundary, in which a significant $\mathbf{B} \times \text{grad } n$ anisotropy should result from the ion intensity gradient between the lobe and magnetosheath. For the south lobe the sense of this anisotropy should be from dusk to dawn, as is observed by the EPAS instrument immediately prior to the magnetopause crossing. The energetic ion data therefore appears to be consistent with expectations based on the locally closed nature of the magnetopause, as concluded by Gosling et al. for this case.

The second crossing during this period shows quite different characteristics in each of the data sets. The plasma and field parameters change much more slowly - the plasma density and tailward velocity decrease with increasing distance from the magnetopause, whilst the temperature slowly rises. The magnetic field strength is also anticorrelated with plasma density. Gosling et al. (1984) conclude that this crossing is of a locally open magnetopause, where the interconnection of lobe and sheath magnetic field allows sheath plasma to penetrate well into the lobe. The energetic ions show a similar gradual decline in intensity as the spacecraft moves further into the lobe. If these ions are penetrating only one gyroradius from the magnetopause, the magnetopause must necessarily be moving very slowly relative to the spacecraft, in order to maintain the slow variation. However, the angular distributions of Figure 5.8 indicate that this is not the case, since the dusk-dawn anisotropy associated with this scenario is absent during the intensity variation. Rather, a transition to a more pancake-like distribution characteristic of the lobe is evident as soon as the spacecraft crosses the magnetopause (plot D), although the tailward flowing ions (Sector 1) are much stronger than in the typical pancake-like

distributions, which are again achieved once the spacecraft has moved well away from the magnetopause (plot E). The slow variation in the ion intensity after the magnetopause crossing and the lack of significant dusk-to-dawn anisotropy suggests that the sheath energetic ions do have access to the lobe in this case, consistent with the apparent open nature of the magnetopause at this point.

The final interval of data that we shall study in this section occurred on February 5th 1983, when ISEE-3 was again located at about 220 R_E downtail from the Earth. This period is distinct from the previous examples in that it occurs some 48 hours after the onset of a large solar particle event, when the fluxes of energetic ions in the solar wind (and subsequently the magnetosheath) suddenly rose by about 5 orders of magnitude. These particles are ejected from the sun during the eruption of a large solar flare, and their arrival at the Earth is generally marked by the passage of an associated interplanetary shock. The enhanced fluxes decay over a period of days from the initial sudden onset, such that the solar wind and magnetosheath fluxes are still several orders of magnitude above the normal solar wind flux on 5th February, two days after the initial onset. Figure 5.9 shows the field and plasma data for the period 0700 to 0900 UT on this day. From the start of this interval until about 0730 UT the spacecraft is located in the magnetosheath, and then briefly encounters the plasma sheet ($\approx$ 0730–0740 UT) before emerging into the lobe, where it remains until $\approx$ 0802 UT. At this time the spacecraft moves briefly back into the magnetosheath once more, and then reenters the plasma sheet. At 0824 UT it moves back out into the sheath. The energetic ion data for this period are shown in Figure 5.10. Note that the fluxes in the sheath (0700–0730 UT and 0824–0900 UT) are higher than in the previous cases described by about an order of magnitude, and that the differences in the fluxes between adjacent energy bands are also smaller. This indicates that the spectrum of the ions in the sheath is much harder in this case. The ion intensity in the lobe (0740–0802 UT) is also much higher ($I > 30 \text{ (s cm}^2 \text{ sr keV)}^{-1}$ for ions of 35–56 keV) than observed in the lobes in the previous cases. The spectrum in the lobe also appears to be harder than that observed in the previous cases, and is slightly harder than that of the reconnection-produced ions observed in the plasma sheet (0730–0740 and 0802–0824 UT). The letters at the top of the plot again refer to the times of the sector plots for this period, which are shown in figure 5.11. These show that the magnetosheath contains a convecting

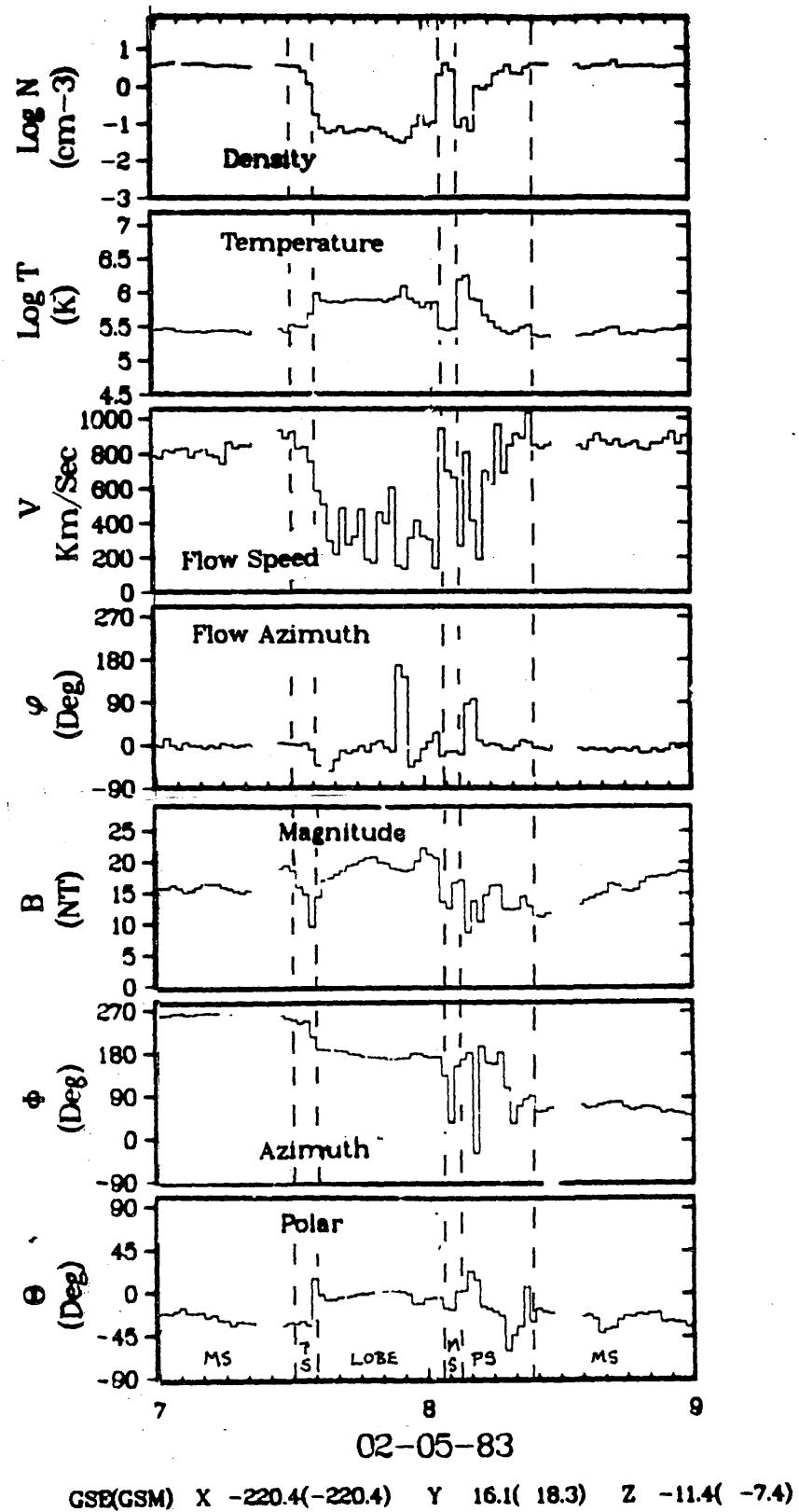


Figure 5.9 Field and plasma data for the period 0700 - 0900 UT on 5th February 1983, in the same format employed previously. This period occurred two days after the onset of a large solar particle event. The regions encountered by the spacecraft are marked at the bottom of the figure.

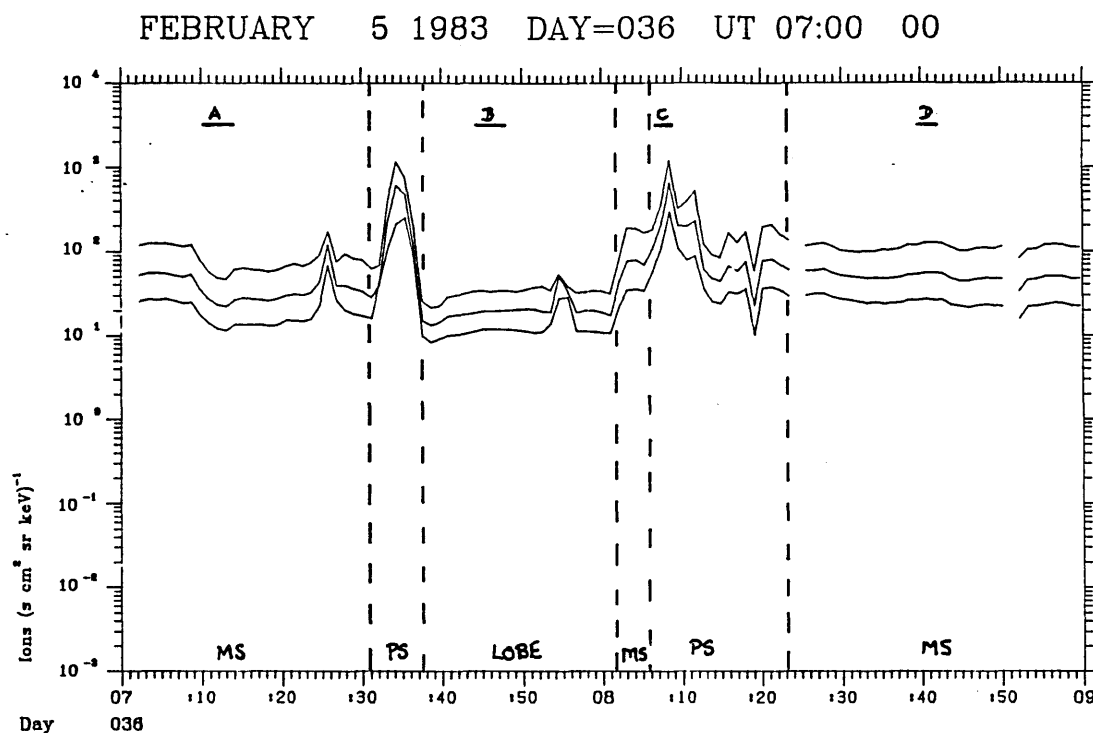


Figure 5.10 Direction averaged energetic ion fluxes from the lowest 3 EPAS energy channels for the same period described in Figure 5.9, during the period of ion flux enhancement associated with a large solar particle event. The fluxes in the sheath and lobes are higher than those observed in the previous events studied, and the spectrum appears harder. The horizontal bars at the top of the figure indicate the times of the EPAS sector plots in the following figure.

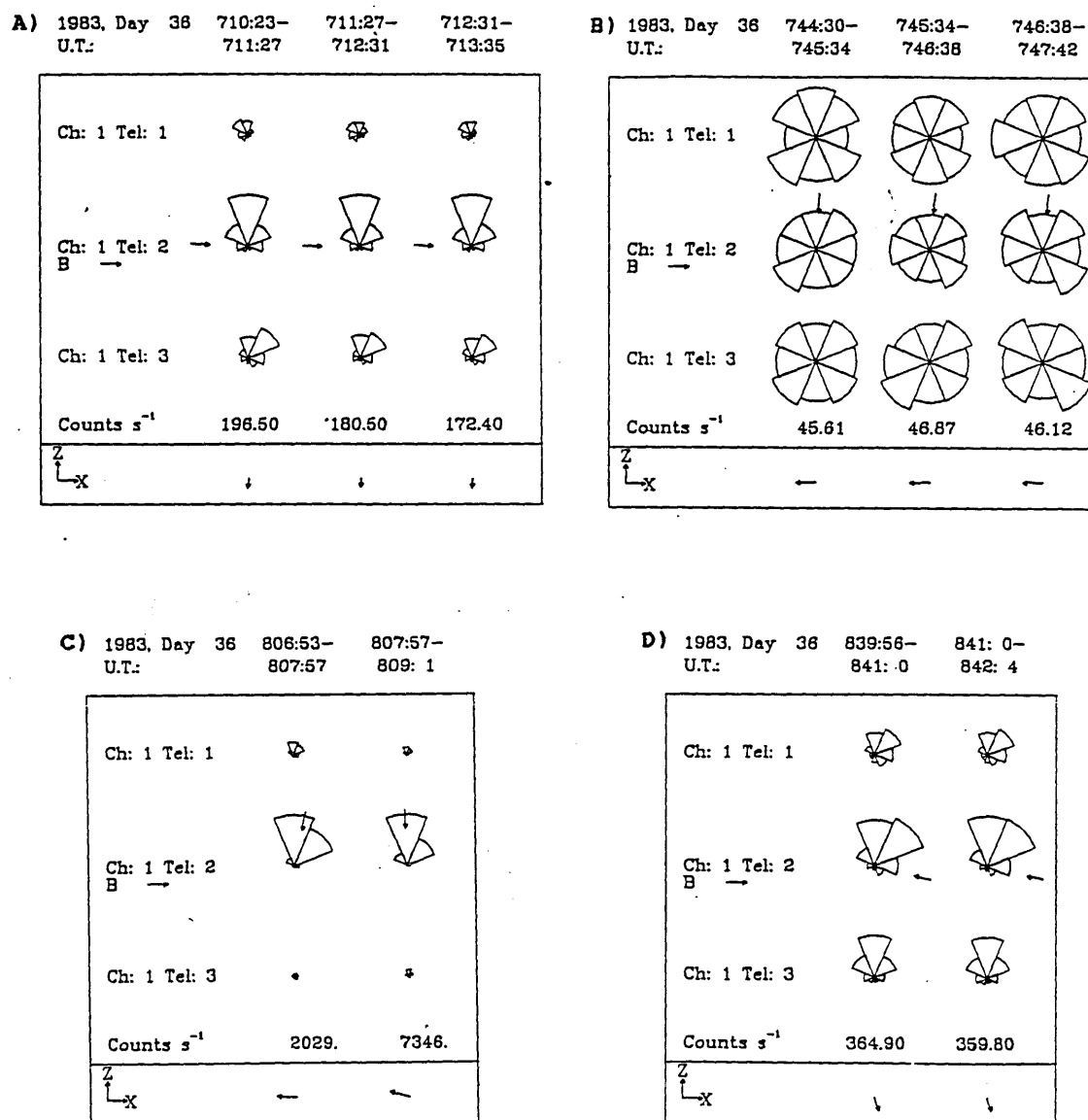


Figure 5.11 EPAS sector plots for the periods marked by the horizontal bars in the last figure, in the same format as employed previously. Panels (A) and (D) are taken when the spacecraft is located in the magnetosheath, and show the convecting distribution observed in the previous case, although the maximum count rates are much higher. Panel (C) shows the beam type distribution in the plasma sheet. Panel (B) shows the distribution in the lobes in this case. Unlike the previous cases, where "pancake" distributions were observed, the distribution in the lobes during solar particle events is closely isotropic, with approximately equal counts in each telescope/look-direction combination.

distribution as before, (panels A and D), whilst the plasma sheet (panel C) shows a strong tailward beam nature, as expected. However, the lobe distribution is significantly different from the previous cases. Panel B shows that this distribution is closely isotropic, with approximately equal counts in all telescopes, and all look directions.

Summarizing the data presented in this section, we have shown that the distribution function of the energetic ions within the lobes is generally peaked at pitch angles closely perpendicular to the direction of the magnetic field, with a small downtail anisotropy in the field aligned flow, such that slightly more particles are convecting tailwards than Earthwards. This is true except during times when the solar wind and sheath fluxes are enhanced by the presence of flare associated solar particles, when the lobe distribution displays a closely isotropic nature.

The apparent similarity of the hardness of the lobe and magnetosheath spectra, and the leakage of ions through regions of open magnetopause strongly suggests that the magnetosheath ions represent the source of the lobe ions, despite the fact that the sheath intensities are generally at least an order of magnitude above those in the lobe at these distances downtail. We shall assume this to be the case in the modelling work that follows in the next sections, when we shall be attempting to reproduce theoretically these observed features of the lobe data.

4. The Magnetosheath as the Source of Energetic Particles in the Deep Tail Lobes.

The distribution function $f(v_{\parallel}, v_{\perp})$ of energetic particles within the lobe is governed by the properties of the region of space acting as a source for these particles and the nature of the interaction of the particles with the boundary between this region and the lobe. The observations discussed in the last section suggest strongly that the magnetosheath is the source of such ions (in agreement with the magnetosheath source for thermal plasma described by Pillip and Morfill, 1978), and in the next section we will see how the trajectories of particles within the lobe magnetic field map back to points of entry, or source points, at the tail magnetopause at some distance downtail from the Earth, depending on the pitch angle of the particle at the measuring point. The lobe distribution therefore depends on the characteristics of the source

distribution in the magnetosheath, the nature of the tail magnetopause boundary between the two regions, and the physics of the particle transmission across it, as well as the subsequent motion of the particles in the lobe. In this section we shall therefore discuss the properties of the magnetosheath region adjacent to the tail lobe, and the processes governing particle entry across the tail magnetopause and into the lobe.

As indicated in the last section the omnidirectional intensity of energetic ions in the magnetosheath is 1-2 orders of magnitude higher than those fluxes measured within the lobes, although there are considerable variations in the flux levels within this region. Further, analysis of data from the solar wind upstream of the bow shock shows that the sheath flux is enhanced by a similar factor above the solar wind energetic ion intensity, with the exception of short duration high intensity bursts. It is evident therefore that there is some process occurring Earthward of the ISEE-3 location in the deep tail ($X_{GSE} > -100$ RE) which results in enhanced energetic ion fluxes in the region between the bow shock and the magnetopause. Several processes have been suggested as causes of such enhancements. The first of these is energization of particles at the bow shock itself (Asbridge et al., 1978). Crooker (1981) showed that energetic ions were present on magnetosheath flux tubes only when the angle between the bow shock surface normal and the interplanetary magnetic field at the point at which the plasma streamlines intercept the shock is less than a certain critical value. This is consistent with acceleration of particles by the Fermi mechanism in the turbulent field regions associated with quasi-parallel bow shocks described by Lee (1982). This process may, in part at least, be responsible for the variable nature of the magnetosheath ion flux. The second process that may account for these observations is the escape of energetic particles from the ring current across the near Earth magnetopause, either during dayside reconnection, or by some "leakage" process. Clearly, as ring current flux tubes become open as a consequence of dayside reconnection, particles must escape from the magnetosphere into the sheath, and have been observed to do so by e.g. Scholer et al. (1981). However, particles may also escape (or "leak") from the magnetosphere by grad-B loss from closed flux tubes (Anagnostopoulos et al. 1986; Sibeck et al., 1987).

The highly turbulent nature of the shocked field in the magnetosheath is likely to scatter a reasonable proportion of particles escaping from the magnetosphere, resulting in a slow diffusion of particles away from the magnetopause as the

flux tubes are convected tailwards, resulting in a convecting population in the magnetosheath - as is observed - rather than a free streaming population. It is therefore possible for back-scattered ions with a ring current source to re-encounter the magnetopause at some point further tailwards. The spatial extents of the ions produced by each method are illustrated schematically in Figure 5.12, which shows a north-south slice through the bow shock (the solid parabola), the magnetosheath and the magnetosphere (bounded by the dashed line, representing the magnetopause). The fine arrowed lines represent the field threading through the system. The dotting in the left hand panel represents the regions of space into which ions produced at the bow shock may permeate. The second diagram shows the spatial extent of those ions that have escaped from the ring current source. The density of the dotting at different points in each case qualitatively matches the anticipated density of the ions at that point.

The relative importance of all these processes is the subject of current debate within the literature (e.g. Sarris et al. 1987, Sibeck et al. 1987b) which is beyond the scope of the discussion here. However, it should be noted that they all lead to similar effects within the distant downstream magnetosheath, specifically that the flux intensity of the energetic ions is highly enhanced over solar wind levels close to the Earth, and then drops off with increasing distance downstream, returning gradually to the level of the solar wind fluxes. In the case of the remnant of the escaped ring current distribution, this is due to the continual diffusion of particles away from the magnetosphere as discussed above. Although diffusion is important in the case of ions produced by energization at the bow shock, it is also evident that sheath particles detected in the nearer Earth magnetosheath have streamlines that intersect the bow shock close to the nose of the shock, where the acceleration process is likely to be most efficient. The trajectories of those particles adjacent to the deep tail magnetopause map back to the bow shock at locations further downwind where the shock may be less well defined (i.e. $\delta V/V$ of the solar wind plasma at the shock is smaller) and the acceleration process weaker, resulting in lower ion fluxes than closer to the Earth.

For the purposes of this study therefore, we shall take a simple assumed dependence for the number density n of energetic particles in the magnetosheath at any point x downstream, such that

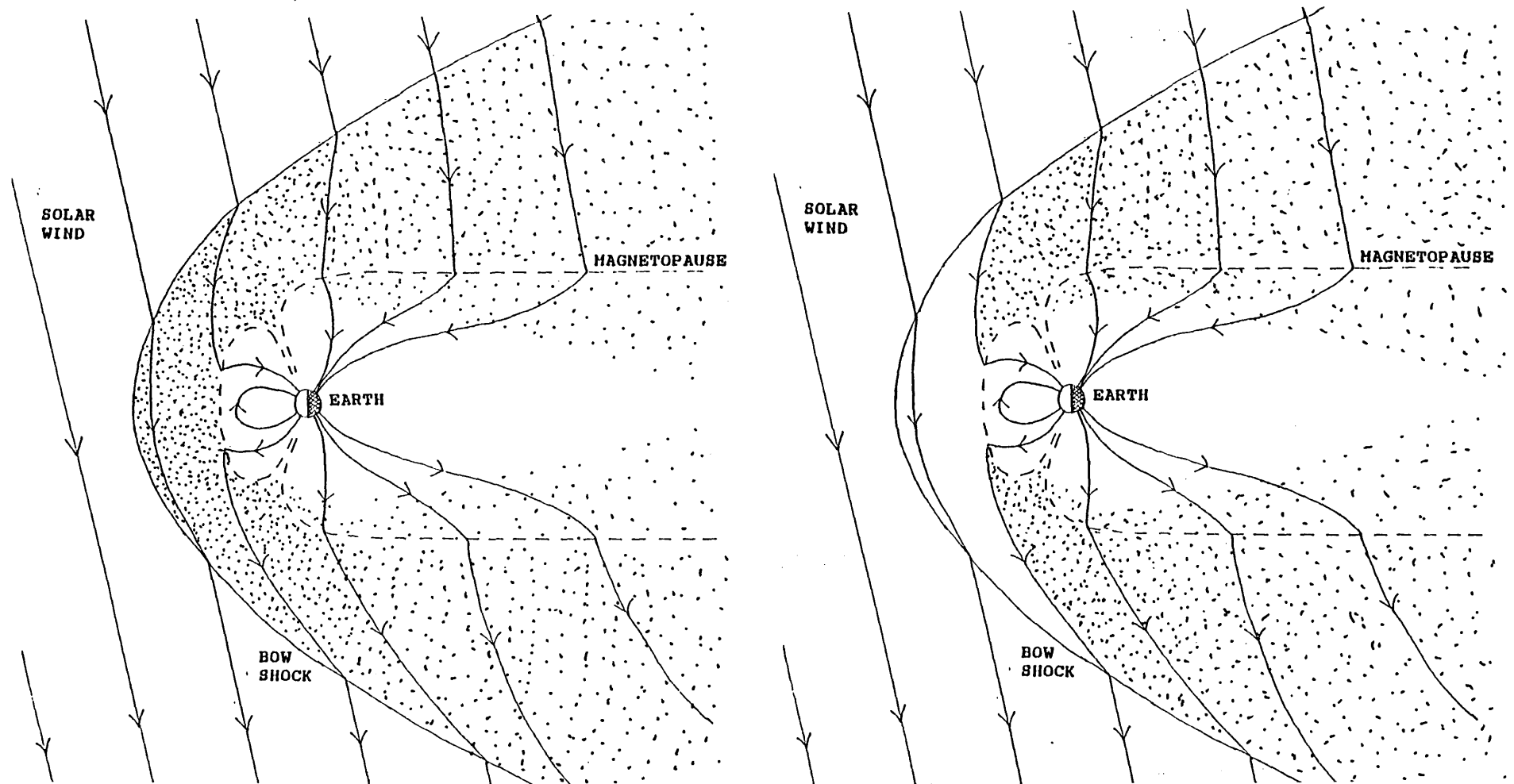


Figure 5.12 Two processes that may be responsible for the formation of a spatial gradient in the magnetosheath ion fluxes. The dotting in the left hand panel indicates the regions of the magnetosheath that may be occupied by particles produced by energization processes at the bow shock, whilst in the right hand panel the dotting denotes the regions that may be occupied by particles that have escaped from the near-Earth ring current across the dayside magnetopause. Both processes lead to similar effects in the magnetosheath along the flanks of the tail, in particular high fluxes close to the Earth, which fall off with increasing distance down the tail.

$$n(x) = N_0 \exp(x/L) + N_{sw} \quad , \quad (5.1)$$

where N_0 is the number density of the Earth/bow shock-associated ions close to the Earth ($x = 0$), L is the scale length of their variation, and N_{sw} is the (constant) background density of the solar wind energetic ions. Note that the data indicates that N_0 should exceed the value of N_{sw} by 2-3 orders of magnitude, except during solar particle events. We shall also assume that the density is constant at any given distance downstream and neglect effects due to temporal flux variations.

Equation (5.1) can be used to describe the variation of the omnidirectional flux with downtail distance. However, the form of the pitch angle distribution of particles measured in the lobes also depends on the nature of the magnetopause separating the tail from the magnetosheath, and the physics of the particle interaction with it, as well as the form of the ion distribution function in the sheath. Firstly, for the purposes of this paper, we shall assume that the particles from the predominant sheath source have complete access to the lobe along the open field lines that thread the tail magnetopause. The Larmor radius of these energetic ($E \geq 35\text{keV}$) ions within the lobe and the adjacent magnetosheath, where the magnetic field strength is usually $\approx 10\text{ nT}$ or less, is approximately one half of an Earth radius (assuming a predominantly proton population). This is large compared to the likely thickness of the magnetopause current sheet, which is of order of a few thermal proton gyroradii ($R_g \approx 1/30\text{ RE}$ for magnetosheath thermal protons with temperature $T \approx 10^6\text{ K}$; e.g. Lui, 1987). For particles of this energy it therefore suffices to model this system as two distinct regions (lobe and magnetosheath) of differing field strength and direction, separated by an infinitesimally thin current sheet. In the rest frame of the magnetic field (i.e. the frame convecting tailward with the magnetosheath flow, in which the convective electric field vanishes, see chapter 2) the trajectories of individual particles may be traced numerically as they move from one field region to the other. The number of particles that are incident on the sheath side of the current sheet, and are then reflected back into the sheath is dependent on the normal component of the field threading the magnetopause, relative to the strength of the transverse components, but this dependence is very weak, except when the normal component is very small. In the limiting case where the normal component vanishes, $B_n = 0$, there can be no transmission of particles between the two regions, except by diffusion, whilst the opposite case, where the normal component is very large compared to the

transverse components, the field lines approximate to straight lines, and particle transmission through the current sheet is total, with no particles reflected. In order to estimate the typical normal component B_n at the tail magnetopause, we note that the field strength $|B|$ in the lobe is of the order 10 nT (see, for example, review by Tsurutani et al, 1986), whilst the radius R_t is of order 30 R_E (e.g. Sibeck et al. 1986) and the length L_t about 1000 R_E (Dungey, 1964). Since the total flux content of the tail lobe ($\Phi = |B| \cdot \pi R_t^2 / 2$ webers) enters the lobe through the tail magnetopause, the average normal component of the field through the magnetopause current sheet is given by

$$B_n = \Phi / \pi R_t L_t = |B| \cdot R_t / 2 L_t = 0.15 \text{ nT.} \quad (5.2)$$

Note, however, that if the open flux occurs in patches across the magnetopause (as would be consistent with flux added to the tail by Flux Transfer Events (FTEs) or sporadic dayside reconnection; e.g. Russell and Elphic, 1978) then B_n in these patches would be larger than this value. The lobe field is thus best represented by a large field component transverse to the magnetopause current sheet ($B_t \approx 10 \text{ nT}$) and a much smaller normal component ($B_n \approx 0.15 \text{ nT}$). The transverse component in the sheath is generally smaller than that in the lobe, and may be orientated in any direction. The component of the field normal to the current sheet must of course be continuous to satisfy $\text{div } \underline{B} = 0$, and is small, but *non-vanishing*, compared to the two transverse components. This latter point is of crucial importance in the context of the work presented in this chapter.

Results from a numerical calculations of the particle motion between two regions with the above field characteristics (i.e. with lobe field strength of 10 nT, and a normal component of 0.15 nT, and with transverse components of the sheath field of 0, 2, 6, and 10 nT at angles of 0° , 45° , 90° , 315° to the lobe field direction) show that although in general each particle crosses the current sheet many times, a large majority of ions incident on the magnetosheath side of the current sheet are transmitted through into the lobe. The only significant departures from this result occur when the transverse component of the sheath field is highly antiparallel to that in the lobe, i.e. there is an extremely sharp change of magnetic field direction between the two regions, when some particles of certain pitch angles may be reflected back into the sheath. The worst case, with the sheath transverse field component exactly

antiparallel to that in the lobe and at the same field strength, results in approximately 50% of particles reflected back into the sheath. However, this figure decreases rapidly as the sheath field strength drops (35% for $B_{\text{sheath}} = 6$ nT, $B_{\text{lobe}} = 10$ nT), and as the fields become less antiparallel (22% with an angle of 135° between the transverse field components, 0% at 90° , for $B_{\text{lobe}} = B_{\text{sheath}} = 10$ nT). However the particular part of the lobe pitch angle distribution which is reduced or missing due to reflection ($f(v_{\parallel}, v_{\perp}) \approx 0$) is found to be very highly sensitive to small variations in the angle between the fields in the two regions. Since, in reality, the sheath field is usually observed to vary rapidly in both strength and direction, this effect is likely to be smoothed out and so does not need to be a major consideration here. Also, we have considered the case of an infinitesimally thin current sheet; if we relax this assumption, such that the current sheet has finite thickness, and the field direction does not change so rapidly, we would expect that even more particles would gain access to the lobe. For the purposes of this work, therefore, it is satisfactory to assume that all particles incident on the current sheet are transmitted through it.

We now need to consider the form of the pitch angle distribution in the magnetosheath and the implications this has for the distribution in the rest frame of the spacecraft once the particles have been transmitted into the lobes. Williams et al. (1988) have recently shown that in the case of a highly variable magnetic field that is typical of the sheath, the energetic ions ($E \geq 5$ keV) have isotropic distributions in the solar wind rest frame, which are then simply convected tailward with the sheath plasma to produce the anisotropies observed in the satellite frame. This implies significant scattering of ions in the magnetosheath, consistent with the diffusion-dominated models for the source of ions in this region described above. In addition, the spectrum of the energetic particles in the solar wind frame may be described by a power law such that

$$\frac{dJ}{dEd\Omega} = k.E^{-\Gamma} \quad (5.3)$$

where $dJ/dEd\Omega$ is the ion differential flux (number of particles per unit area of detector, per steradian of look angle, per unit energy, per unit time), E is the energy of the particles in the solar wind frame, and k is a constant. The parameter Γ is an empirical factor which, for typical conditions in the sheath,

has a value of ≈ 3.5 , although the spectra tend to harden during solar particle events to values of Γ that may even be less than unity (I. G. Richardson, private communication). This is important when considering the difference in the observed lobe distributions between normal, and solar particle event conditions, as will be explained later.

The distribution function f is related to the differential energy flux by the relationship

$$\frac{dJ}{dEd\Omega} = \frac{f v^{*2}}{m_i} \quad (5.4)$$

where v^* is the velocity of the particle in the solar wind frame, and m_i is the ion mass. Eliminating $dJ/dEd\Omega$ between equations (5.3) and (5.4) and rewriting in terms of v^* gives the distribution function in terms of the particle velocity in the solar wind rest frame as

$$f(v^*) = k' / v^{*2(1+\Gamma)} \quad , \quad (5.5)$$

where $k' = k.m_i^{(1-\Gamma)}/2$ is a new constant. The distribution function of the ions in the magnetosheath is illustrated schematically in the top panel of Figure 5.13, showing contours of constant f in velocity space. In this figure the solar wind frame is represented by the axes v_x' and v_z' which are shifted by an amount v_{sw} in the negative v_x' direction relative to the Earth's rest frame (v_x, v_z). This corresponds to the motion of the field line rest frame away from the Earth with the magnetosheath flow at a speed $-v_{sw}$ relative to the Earth's frame. The contours of constant f are represented by the concentric circles about the origin of the solar wind frame (v_x', v_z'). The second part of Figure 5.13 illustrates the portion of this distribution which acts as a source for the lobe distribution. This part of the figure is in the same format as the one above, but we now include the direction of the lobe magnetic field, indicated by the solid line and arrow, making an angle θ with the v_x axis. As described above, the component of the field threading from the sheath into the lobe is small compared to the transverse components, such that the angle θ between the field direction and the x-axis is also small (and shown exaggerated here for clarity). The convective electric field in this frame also vanishes so that there is no acceleration of the particles as they cross the tail magnetopause, so the form of the distribution is unaltered in this frame. However, only the portion of the

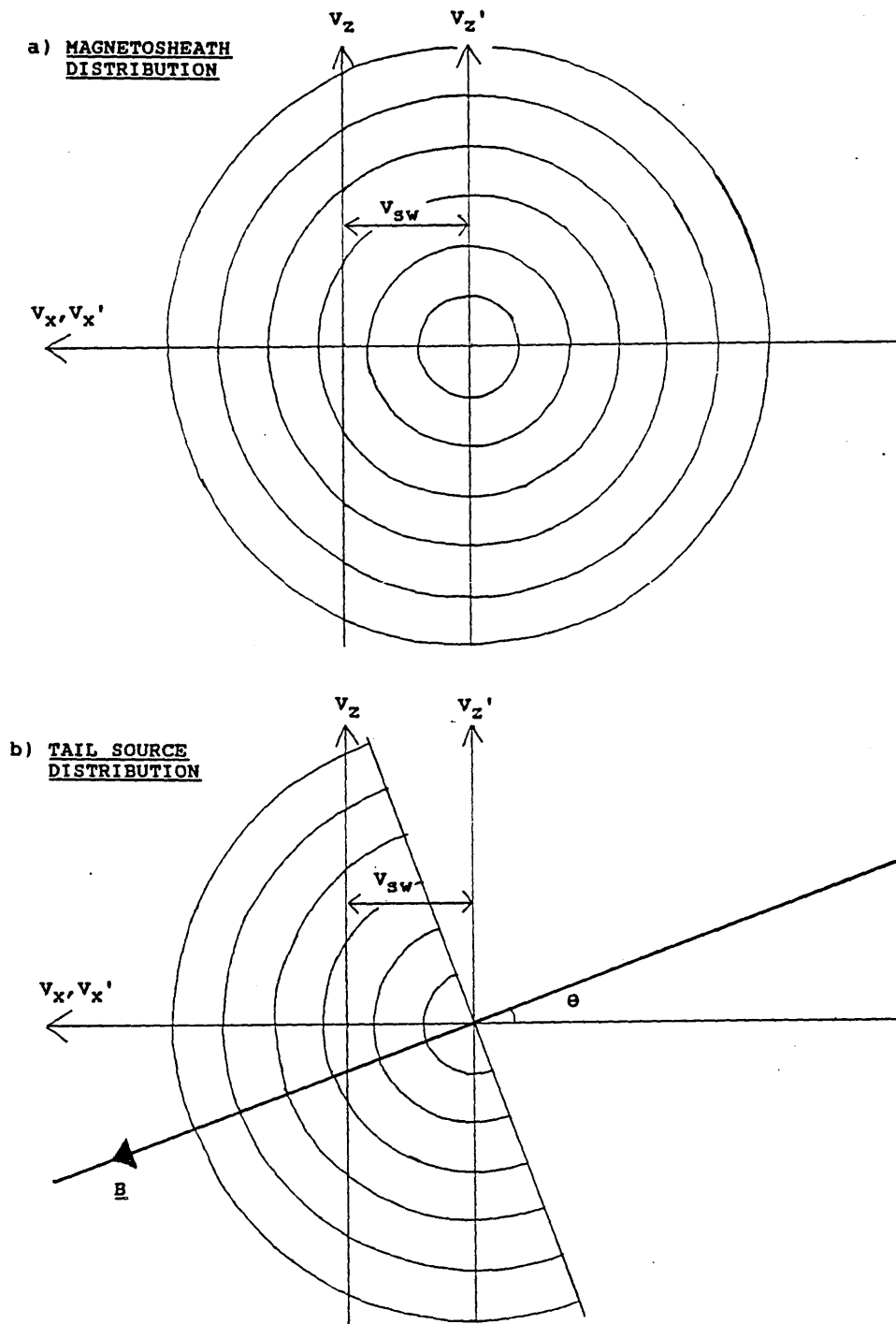


Figure 5.13 Schematic illustration of the distribution of energetic ions in the magnetosheath, and the portion of that distribution which acts as a source for the lobe particles. In each panel the solar wind frame is represented by the axes (v_x', v_z') , and is shifted by an amount $-v_{sw}$ with respect to the Earth's frame (v_x, v_z) . The magnetosheath distribution is isotropic in the solar wind frame, and is represented by a set of concentric circles about the origin of this frame. The lower panel includes the lobe field direction (solid arrowed line at an angle θ to the v_x axis), which is at rest in the solar wind rest frame. In this case the portion of the magnetosheath distribution which has access to the lobe is that portion with a component of velocity along the field line which is in the same direction as the field itself.

distribution which has a positive parallel component of motion in the solar wind frame may move away from the magnetopause and into the lobes, i.e only half of the sheath distribution acts as a source for the lobes, as shown in the figure. In the Earth's rest frame this translates to particle populations that have velocity components in both directions along the field line, depending on which side of the v_z -axis they are located - however those particles with negative v_z are confined to have field aligned speeds which are of order or less than the sheath flow velocity $|v_{sw}|$. Note also that since the sheath distribution is isotropic in the solar wind frame, the value of $f(v^*)$ is dependent only on the speed and not on the pitch angle of the particles in this frame. Hence for particles observed with a given $v_{||}$, $v_{\perp}$ in the lobe, it suffices to calculate the corresponding value of v^* at the boundary to determine the value of $f(v_{||}, v_{\perp})$, since this value is conserved along the particle trajectory by Liouville's Theorem (i.e. pitch angle scattering at the magnetopause is not pertinent).

The transformation of velocities from the solar wind to the Earth's frame is illustrated in the velocity space diagram shown in Figure 5.14. The axes shown are the same as in the previous figure, and the solid arrowed line again represents the lobe field direction. The motion of particles in the Earth's frame can be considered to be made up of three contributions. Firstly, the particles are convected with the field lines as they move in towards the centre of the lobe. This is the $\mathbf{E} \times \mathbf{B}$ drift in the spacecraft rest frame, and is represented by the arrow labelled $v_{E \times B}$ in Figure 5.14. The remaining contributions are the component of motion parallel and perpendicular to the field line direction, labelled $v_{||}$ and $v_{\perp}$ respectively. The corresponding velocity in the field line rest frame is represented by the arrow labelled v^* connecting the origin of that frame with the tip of the combined velocity vector in the spacecraft rest frame. Consideration of the geometry of such a diagram allows the velocity v^* to be expressed in terms of the other (known) parameters,

$$v^* = (v_{\perp}^2 + (v_{||} + |v_{sw}| \cos \theta)^2)^{1/2}. \quad (5.6a)$$

Since θ is small $\cos \theta$ is approximately unity, the above expression may be rewritten

$$v^* = (v_{\perp}^2 + (v_{||} + |v_{sw}|)^2)^{1/2}. \quad (5.6b)$$

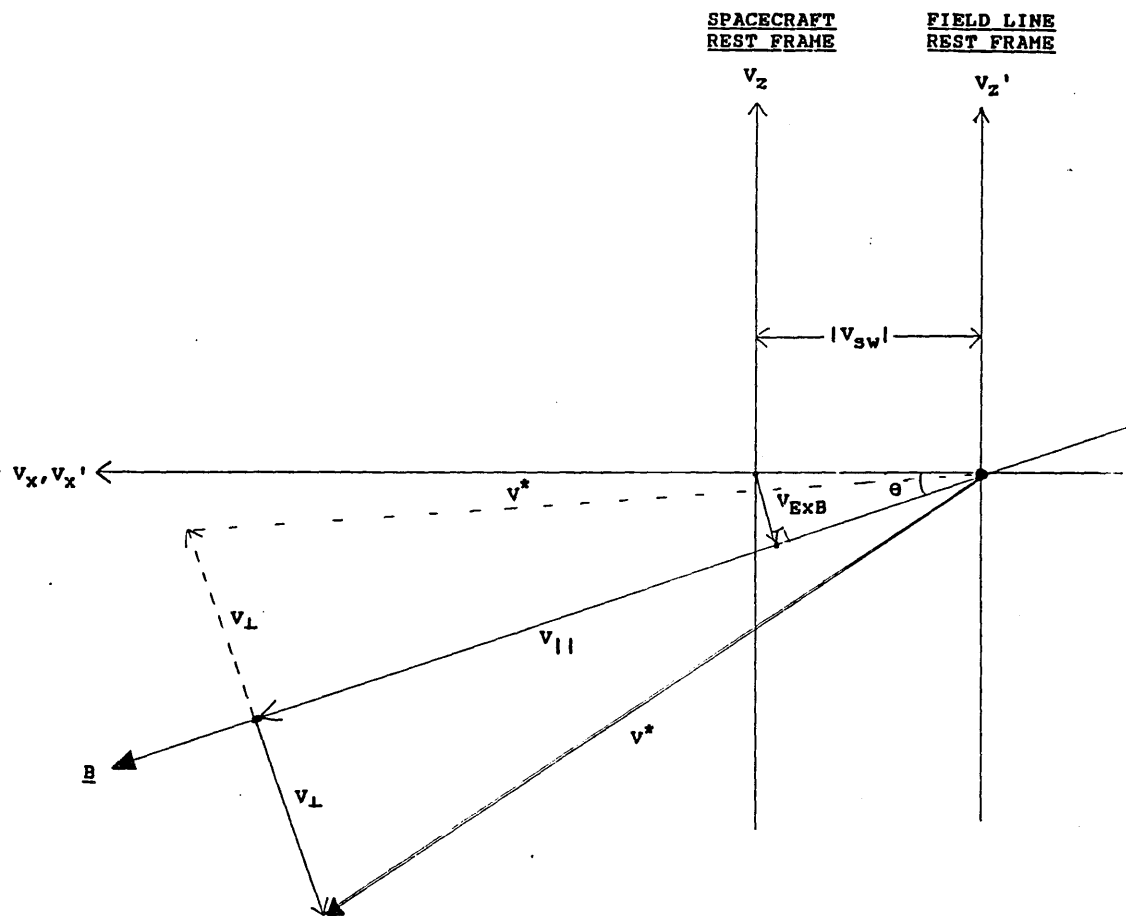


Figure 5.14 The transformation of velocities between the solar wind rest frame and the Earth's rest frame. The axes are the same as the previous figure, and the solid arrowed line again represents the field direction. In the Earth's rest frame the particle's motion is made up of an $E \times B$ drift towards the tail centre plane at speed $v_{E \times B}$, a component of velocity $v_{||}$ along the field direction, and a component $v_{\perp}$ perpendicular to the field direction. The geometry of the diagram can be used to determine the velocity v^* of the particle in the solar wind frame (see equation 5.6a,b)

Equation (5.6) may now be used to replace v^* in (5.5), and by including the effect of the spatial density gradient (equation (5.1)) a general formula for the value of the distribution function for a particle entering the lobes at a position x , with a field aligned velocity $v_{||}$, may be obtained

$$f(x, v) = \frac{k' \cdot n(x)}{(v_{\perp}^2 + (v_{||} + |v_{sw}|)^2)^{(1+\Gamma)}} \quad (5.7)$$

Since the value of the distribution function f is conserved, the value associated with a particular energy and pitch angle of particle at a particular point within the lobe may be determined by tracing back the trajectories of such particles to the lobe magnetopause, to find the position x and speeds $v_{||}$ (and $v_{\perp}$) of entry. From equation (5.7) it follows that particles which enter the lobe close to the Earth will have a higher value of f than those entering further tailward. Also, equation (5.7) gives a larger value of f for those particles which enter the lobes with negative (tailward) velocities than those which enter at the same point and then move Earthward, since the former have smaller values of v^* in the sheath. In the small θ approximation, the maximum tailward field-aligned speed a particle entering the lobe can possess is the speed of the sheath flow, v_{sw} , dragging the lobe flux tubes antisunward, as there must exist a net earthward motion of particles in the field line rest frame for particle entry. Particles entering with Earthward motion in the spacecraft rest frame can have any field aligned velocity. For $\Gamma = 3.5$, typical of the sheath distribution, the ratio of f for particles entering with maximum tailward velocity to those entering the lobe at the same point x , and then moving exactly along the field line (i.e. $v_{\perp} = 0$), is approximately 3 for particles of energy 35 keV, and less than this for higher energies. Hence the source distribution at a given point is not particularly anisotropic in the Earth's frame. The spatial variation of the sheath density is governed by equation (5.1), and depends on the ratio of N_0 to N_{sw} , and the scale length for variation. As explained above, the data indicates that N_0 exceeds the background solar wind flux N_{sw} by several orders of magnitude. Hence the spatial variation of the sheath density also covers a few orders of magnitude, so that the value of f is more strongly dependent on x than it is on the value of $v_{||}$ and $v_{\perp}$, although the latter are still important, especially when the scale length for sheath density variations L is large.

In the next section we shall study the motion of particles within a model lobe with a view to establishing the point at which each particle in the pitch angle distribution crosses the tail magnetopause, and the velocity with which it does so. Using the above analysis for the distribution function of particles at entry, and invoking Liouville's Theorem on the conservation of f , we can construct the pitch angle distribution of the particle population at any point within the model lobe.

5. Motion of Particles in a Uniform-Field Lobe With a Perfect Mirror at One End.

In the last section we saw how the distribution function $f(v_{\parallel}, v_{\perp})$ of the particles just inside the tail magnetopause depends on the down-tail position of entry and the velocity of the particles. By invoking Liouville's theorem on the conservation of $f(v_{\parallel}, v_{\perp})$ along a particles trajectory it is possible to deduce the resultant distribution function at any point in the lobe. The results can then be compared to the observations described above. In this section we shall therefore investigate the motion of particles within a simple model lobe, in order to determine the down-tail position x_i and velocity v_i of the particles at the magnetopause, given that they are later located at some point (x_0, z_0) in the lobe and are moving with velocity v .

We shall, at first, assume the simplest possible model lobe to illustrate the main principles involved in the formation of the pancake pitch angle distributions observed in the lobe energetic ions. In this model we represent the lobe as an elongated box, in which the field is assumed to be everywhere constant, with the exception of the Earthward boundary, taken to be $x = 0$, where a perfect magnetic mirror is applied, corresponding to a infinite step increase of the field strength at this point. Any particle incident on this mirror is perfectly reflected, i.e. its field aligned component of velocity is instantaneously reversed. The field inside the box is tilted through an angle θ relative to the boundary to give a small component B_n normal to this boundary.

The coordinate system and magnetic field structure assumed for this model lobe are illustrated in Figure 5.14. The x -direction is aligned with the Earth-Sun line with the Earth (perfect mirror) located at $x = 0$. All points within the lobe consequently have negative x -coordinates. The z -direction represents the direction normal to the tail current sheet; note that there is no y , or cross tail

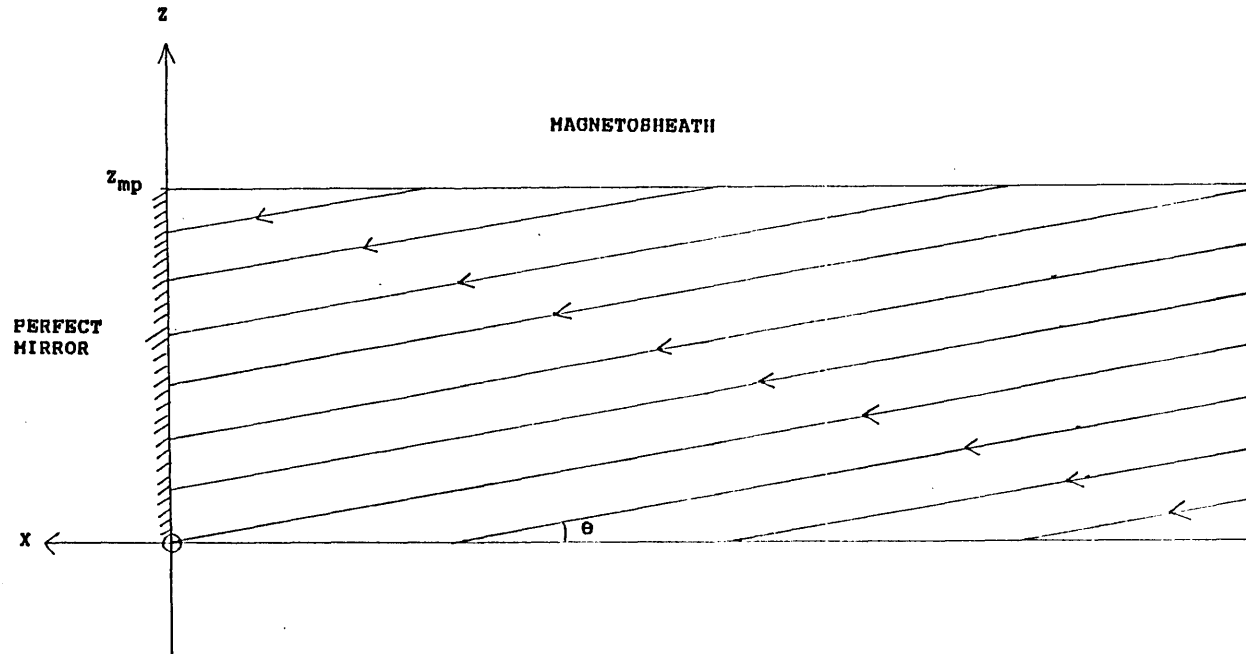


Figure 5.15 The coordinate system and magnetic field structure assumed in the simple model lobe. In this model the x -direction is taken to be aligned with the Sun-Earth line with the Earth located at $x = 0$. Points within the lobe therefore have negative x -coordinates. In the z -direction the lobe is bounded by the tail centre plane at $z = 0$, and by the magnetopause at $z = z_{mp}$. The field in the lobes has a large component in the positive x -direction, and a smaller component in the negative z -direction, such that the field line is tilted through a small angle θ with respect to the x -direction. Each field line thus threads into the magnetosheath at some point along its length. At the Earthward end of the lobe we apply a perfect mirror, which we assume to reflect all incident particles.

dependence in our model. The model is bounded in the z -direction by the tail centre plane at $z = 0$, and the magnetopause is located at $z = z_{mp}$. The x -component of the field, B_x , is assumed positive and to be considerably larger in magnitude than the z -component, $-|B_z|$, so that the angle θ between the x -axis and the field direction is small, and to a first approximation, the field in this lobe points towards the Earth (Note that B_x reverses sign in the other lobe so the field points away from the Earth - however the Earthward/tailward direction of the field is of no importance to the particle kinematics within the lobes). Each field line therefore threads into the magnetosheath at some point along its length, where the component of the field threading the boundary $B_n = -|B_z|$. The sheath plasma is assumed to move tailwards with the solar wind speed, v_{sw} (taken to be positive in the negative x -direction) at all points along the tail magnetopause, and hence the point at which any particular field line crosses the magnetopause also moves tailward at this speed. This tailward motion of the field at the magnetopause results in a convection of the field lines in the lobe towards the tail centre plane at a speed $v_z = v_{sw}B_n/|B|$, considerably smaller than the sheath flow speed, and also sets up a convection electric field across the tail lobe $E_{tail} = v_{sw}B_n$.

Energetic particles within the lobe move, for the most part, towards or away from the Earth along the field direction, but also have a small $\mathbf{E} \times \mathbf{B}$ drift towards the tail centre plane ($z = 0$), at a speed given by $E_{tail}/|B|$. The guiding centres of the particles therefore move towards the tail centre plane at the same speed as the field lines. Further, there are no grad-B , or curvature drifts within this model, nor do the guiding centres experience any form of acceleration within the lobes, or at the magnetic mirror, other than that which reverses the field aligned velocity of the particles.

We will now consider the x -component of the velocity of a particle of energy E and pitch angle α , arriving at a point (x_0, z_0) within the lobe at a time $t = 0$ ($\alpha = 0$ corresponds to a particle moving directly along the field line towards the Earth in this case). As mentioned above, all x -positions within the lobe are negative, and we shall take particle velocities to be positive in the positive x -direction. From the geometry of the field described above, it follows that this particle has its guiding centre along the field line that crosses the magnetopause at a position

$$x_{fo} = x_o - \frac{B_x}{|B_z|} (z_{mp} - z_o) \quad . \quad (5.8)$$

Since this point is being convected tailwards by the sheath flow at a constant speed v_{sw} , at any other time t the field line cuts the magnetopause at the point

$$x_f(t) = x_o - \frac{B_x}{|B_z|} (z_{mp} - z_o) - v_{sw}.t \quad . \quad (5.9)$$

Considering also the motion of the particles in the x -direction, the x position of the particle in the lobe at a time t (provided that it has not interacted with the perfect mirror) is simply given by the equation

$$x_p(t) = x_o + v_{||} \cos \theta .t \quad . \quad (5.10)$$

Since θ is small, $\cos \theta$ is approximately unity, and $v_{||}$ is given by

$$v_{||} = \sqrt{(2E/m_i)} . \cos \alpha \quad (5.11)$$

where E , m_i , α are the energy, mass and pitch angle of the particle respectively. The motion of the particle in the z -direction does not need to be explicitly considered in order to find the point at which it crosses the magnetopause; since the particle is confined to a single flux tube as a consequence of its $\mathbf{E} \times \mathbf{B}$ drift, it follows that when the particle x -coordinate matches that of the field line/magnetopause intersection point at some time t the particle must be located at the magnetopause, leaving the lobe if t is positive, or entering if t is negative. It is this latter case in which we are interested. One further complication arises from the possibility that the particle has undergone a reversal of its motion at the perfect mirror at $x = 0$ at some earlier time t_m (negative). This has happened to particles arriving at (x_o, z_o) which are moving tailwards with velocities that are not small compared to the sheath flow speed. The limiting value of field aligned velocity separating those particles which have mirrored from those which have not is given by the field aligned velocity of the particle which enters the lobe at $x = 0$ and then drifts to the point (x_o, z_o) , i.e. the particle which is located at $x = 0$ at the same time as its field line crosses the magnetopause at $x = 0$. Putting $x_f(t) = x_p(t) = 0$ in equations (5.9) and (5.10) and eliminating t , (i.e. equating the time taken by the particle to travel from $x = 0$ to x_o at speed v_L to the time taken for the field line to travel

to $x_f(t = 0)$ at speed v_{sw}) we obtain an expression for the limiting field aligned velocity

$$v_L = \frac{-v_{sw}x_0}{(x_0 - (z_{mp} - z_0).B_x/|B_z|)} \quad (5.12)$$

For particles of energy E this corresponds to a limiting pitch angle α_L given by

$$\alpha_L = \cos^{-1} \{ v_L \sqrt{m_i/2E} \} \quad (5.13)$$

All particles with pitch angles greater than this value must have interacted with the perfect mirror before reaching the point (x_0, z_0) . Note that if E is large such that the particle speed $V \gg v_{sw}$, the value of α_L will be close to 90° . Since we have assumed that the mirror simply reverses the particles' field-aligned motion, the source points for particles which have mirrored can be calculated by noting that the time t_m at which each particle interacts with the mirror can be deduced by putting $x_p(t_m) = 0$ in equation (5.10), giving

$$t_m = -x_0/v_{||} \quad (5.14)$$

and its subsequent motion is thus given by

$$x_p(t) = v_{||} (t - t_m). \quad (5.15)$$

We therefore have a set of simple equations describing the motion of particles in the lobe x-direction. Using the fact, noted above, that particles located at the same x-position as their field line/magnetopause crossing point must be entering the lobe (if t is negative), it is possible to calculate the entry points of particles for any value of pitch angle and energy.

Some of the trajectories of the guiding centres of energetic particles (with $V \gg v_{sw}$) within the model lobe are illustrated in Figure 5.16, using the same coordinate system as employed in Figure 5.15. Figure 5.16 shows a single field line (solid arrowed line) within the lobe, passing through the measuring point (x_0, z_0) at $t = 0$. The solid horizontal line crossing the z-axis at z_{mp} represents the tail magnetopause, whilst the thin arrowed lines represent the trajectories of particles of a given speed, but of varying pitch angle, which reach (x_0, z_0) . The first, which intersects the magnetopause at $z = z_{mp}$ at the point $x_{\alpha 1}$, represents

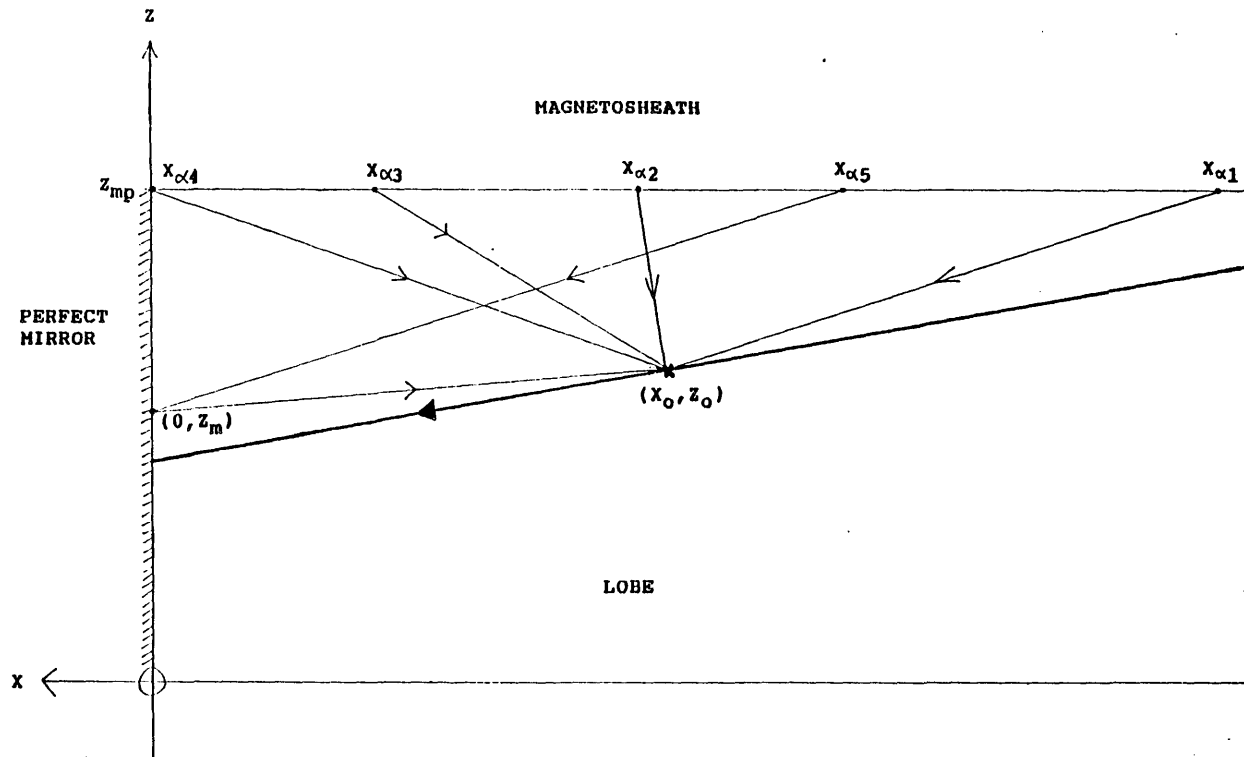


Figure 5.16 Energetic ion trajectories within the simple model lobe. In this figure we show a single field line (heavy arrowed line) for clarity. The lighter lines indicate the trajectories of the guiding centres of a number of particles, of different pitch angles, to the measuring point (x_o, z_o) . The first trajectory, that of a field aligned particle, crosses the magnetopause at $X_{\alpha 1}$, and then moves Earthward to (x_o, z_o) . A particle of 90° pitch angle crosses at $X_{\alpha 2}$ and $E \times B$ drifts towards the tail centre plane. The limiting pitch angle separating those particles which have mirrored from those which have not is given by the particle that enters the lobe at $X_{\alpha 4}$ and drifts tailwards to the measuring point. All particles with pitch angles above this value, for example the anti-field aligned particle which originally enters the lobe at $X_{\alpha 5}$ have mirrored before reaching (x_o, z_o) . Since we apply a spatial gradient in the magnetosheath source distribution, the value of f is highest for the particles entering closest to the Earth, and these give the peak in the pitch angle distribution. Further, since the anti-field aligned particle enters the lobe closer to the Earth than the field aligned particle, a down tail anisotropy will also result.

a particle with zero pitch angle. This particle enters the lobe when the field line shown crosses the magnetopause at the point $x_{\alpha 1}$, and subsequently moves along the field line towards the Earth, and is convected inwards with the field line as the latter is convected tailward by the sheath flow. The trajectory is a straight line since all velocity components are constant in this model. Since this particle has the maximum field aligned speed for ions of this energy, the point $x_{\alpha 1}$ is the furthest downtail source point contributing particles to the distribution at (x_0, z_0) . The second trajectory shown is that of the 90° pitch angle particle. This particle has no field aligned component of velocity, and simply drifts inwards with the convection of the field, as indicated by the trajectory crossing the $z = z_{mp}$ magnetopause at $x = x_{\alpha 2}$ (note that in the $\cos \theta = 1$ approximation $x_{\alpha 2} = x_0$). Again, this particle entered the lobe when the field line was incident on the magnetopause at this point. The third trajectory, crossing the magnetopause at the point $x_{\alpha 3}$ represents the trajectory of a particle with pitch angle a few degrees larger than 90° . This particle moves slowly tailward as the field convects toward the tail centre plane, at a speed somewhat less than the magnetosheath flow speed v_{sw} . The trajectory shown connecting the points $(0, z_{mp})$ to the measuring point (x_0, z_0) represents the limiting trajectory of the particle whose pitch angle α_L is given by equation (5.13). This particle has the maximum pitch angle possible for a particle to reach (x_0, z_0) without having first interacted with the perfect mirror, and entered the lobe at the same time as the field line first entered at the point $(0, z_{mp})$.

Note that all particles following the trajectories so far described reach the point (x_0, z_0) with the same field aligned speed $v_{||}$ with which they first entered the lobe. This is not true of the remaining trajectory, which represents the course taken by a particle with a pitch angle of 180° . Like all particles with pitch angles greater than that given in equation (5.13), this particle has had its motion reversed at the perfect mirror, which it hit at the point $(0, z_m)$ at a time t_m previously. Since its field aligned velocity was reversed at this point, it follows that previous to the interaction with the mirror this particle had the same components of velocity to the particle first described, which entered the lobes at $x = x_{\alpha 1}$ (i.e. the particle with zero pitch angle). Hence the part of the trajectory of this particle undertaken before the interaction with the perfect mirror is parallel to the trajectory of the corresponding field aligned particle described above. Since the 180° particle has a longer path to the point (x_0, z_0) than the field aligned particle, but the same speed, it must have spent longer in

the lobe, as is evident from the geometry of Figure 5.16, and consequently crossed the magnetopause at a position closer to the Earth. The entry velocity is opposite in sign to its subsequently measured velocity.

The equations (5.8) to (5.15) can be used to calculate these points of entry to the lobes of particles with each value of pitch angle. Since the field in this model lobe is uniform, the field-aligned velocity of each particle is unchanged between its point of entry and its point of detection, except for those particles that have mirrored at $x = 0$. In the latter case the parallel velocity is simply reversed in sign. The value of the distribution function f for each particle can then be deduced from the calculated values of x and $v_{||}$, as explained in the previous section. Under typical conditions (when $N_0 \gg N_{sw}$ in equation 5.1) those particles which have source points close to the Earth have the highest values of f since the assumed energetic ion density in the sheath is largest at these points, whilst those from source points further tailwards have correspondingly lower values of f . The peak in the resultant pitch angle distribution is therefore located at the limiting pitch angle, given by equation (5.13), which represents the pitch angle of the particle originating at $x = 0$. The pitch angle distribution falls smoothly away from this point as the source points are located further downtail for both higher and lower pitch angles. The minimum in the distribution is located at zero pitch angle, since this is the furthest tailward source point, as explained above. The distribution is also asymmetric, firstly due to the limiting pitch angle having a value higher than 90° , but also since those particles moving tailwards, which have mirrored at $x = 0$, have source points nearer to the Earth than the corresponding particles which have not yet mirrored.

Since the value of f is conserved as the particles move in the lobe, the pitch angle distribution at any point within the lobe can be deduced from the entry point and velocity using equation (5.7). Some distributions obtained using this method are illustrated in Figure 5.17, showing values of f against pitch angle, from 0° to 180° , at a position taken to be $100 R_E$ tailward of the perfect mirror. The spatial variation of the energetic ion density in the sheath is assumed to fall from $N_0 = 500 N_{sw}$ to the background level N_{sw} with a scale length $L = 100 R_E$ (cf. equation (5.1)). In the first panel the measuring position is taken to be $5 R_E$ from the magnetopause position (i.e. $z_{mp} - z_0 = 5 R_E$). The solid plot in this figure represents the distribution obtained by assuming the above parameters in our model, whilst the dashed plot shows the distribution that

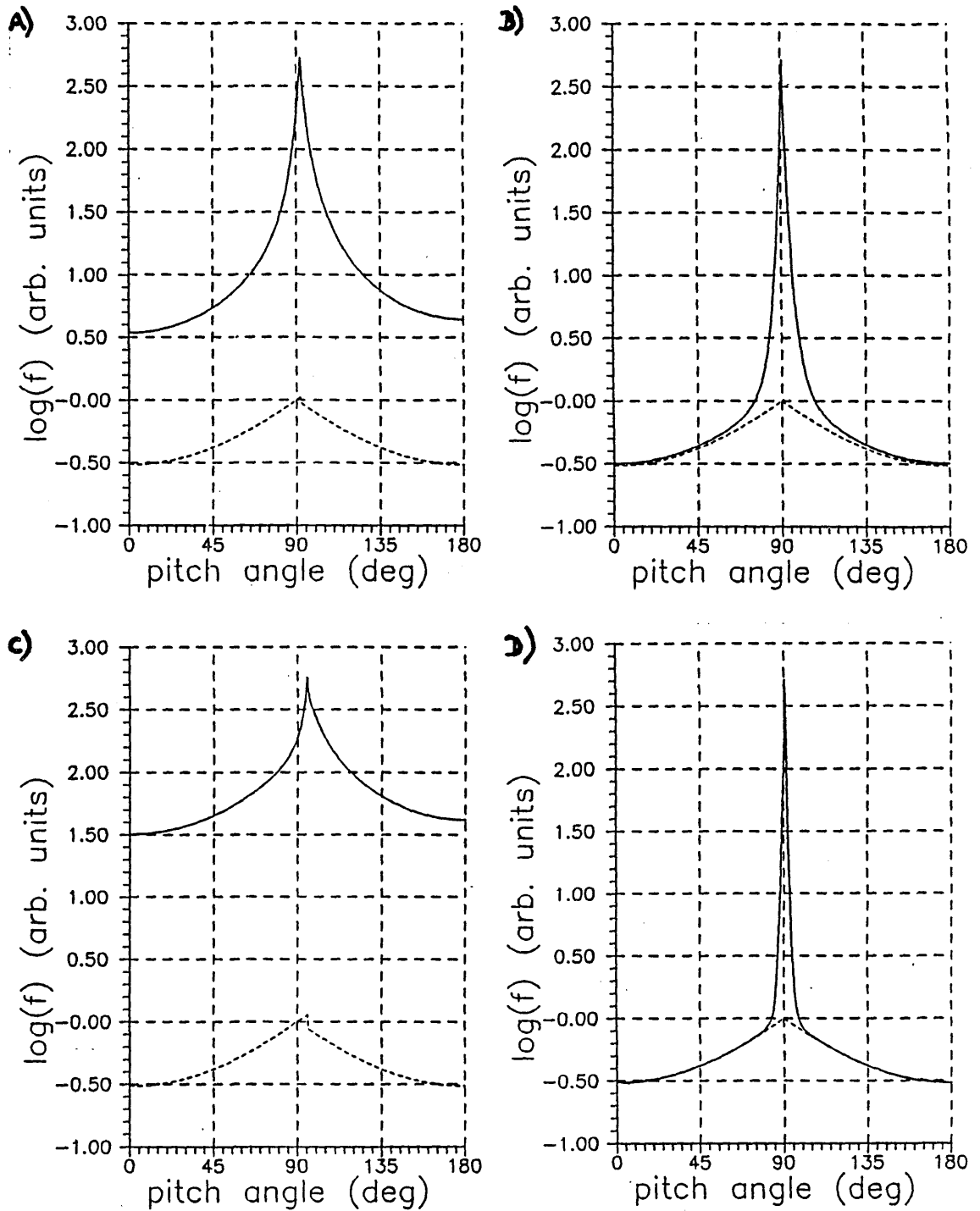


Figure 5.17 Plots of distribution function f against pitch angle at a position $100 R_E$ downtail from the perfect mirror in the model lobe. In these plots the peak magnetosheath density N_0 is taken to be 500 times the solar wind background density N_{sw} , and the sheath density falls off with distance down the tail with a scale length for variation of $100 R_E$. The solid line in plot (A) represents the distribution expected at $5 R_E$ from the magnetopause, and will be used as a reference distribution. The dashed lines represent the distribution expected if there is no near-Earth enhancement of the source fluxes. The distribution in this case is peaked a few degrees above 90° , and the value of f is higher for those particles with higher pitch angles than those with lower pitch angles, giving the required downtail anisotropy. The remaining panels show the effect of distance of the measuring point from the magnetopause and show the distributions at $15 R_E$ (panel B), $1 R_E$ (panel C) and $25 R_E$ (panel D). As the measuring point moves away from the magnetopause the peak in the distributions moves to pitch angles closer to 90° , and the degree of anisotropy and the omnidirectional flux (as represented by the area under each curve) reduce.

would be obtained if there were no enhancement of the sheath flux above the background level N_{sw} (i.e. assuming a uniform density N_{sw} along the entire length of the tail magnetopause). In the latter case, the variation in the pitch angle distribution results solely from the field-aligned entry velocity of the particles, such that there is little difference in f for the 0° and 180° particles. The panel shows that the modelled pitch angle distribution of the lobe particles is quite highly peaked above the solar wind background at values of pitch angle a few degrees greater than 90° . This peak in the distribution is at the pitch angle give by equation (5.13), since this particle comes from a source position closest to the Earth. It also has the greatest tailward velocity of all particles detected at (x_0, z_0) at its point of entry to the lobe. Both of these effects lead to higher value of $f(v_{||}, v_{\perp})$ as described in the last section. For pitch angles below this maximum, it can be seen from Figure 5.16 that the source point is further downtail as the pitch angle decreases from the maximum, and the entry velocity becomes more positive (Earthward), leading to a falling off of the value of $f(v_{||}, v_{\perp})$. For pitch angles above the maximum, for which particles have all mirrored, the same is true, and there is also a steady fall in $f(v_{||}, v_{\perp})$, although the source points of these particles are closer to the Earth than the corresponding low pitch angle particles, so that the values of $f(v_{||}, v_{\perp})$ are slightly higher for the mirrored than the non-mirrored particles. This theoretically produced pitch angle distribution plot thus includes the basic features observed in the ISEE-3 data set, in that the distribution is peaked close to 90° (closer than is resolvable with the 8 azimuthal sector bins), and also shows the downtail anisotropy, with particles moving tailward ($\alpha > 90^\circ$) having higher values of $f(v_{||}, v_{\perp})$ than the corresponding Earthward moving particles ($\alpha < 90^\circ$). The remaining panels of Figure 5.17 show how these pitch angle distributions depend on position within the lobe, and we shall be returning to discuss these in detail later.

The effect of distance of the measuring point from the magnetopause on the expected pitch angle distribution can be seen by considering Figure 5.18. This figure is of the same format as figure 5.16, but the measuring point is located at a greater distance from the magnetopause than before. The relative position of the magnetopause in the last figure to the measuring point is shown as a dotted line for reference. The trajectories shown are for the same pitch angles considered in the previous figure, and it is important to note that these trajectories are unchanged with respect to the measuring point (x_0, z_0) . Each

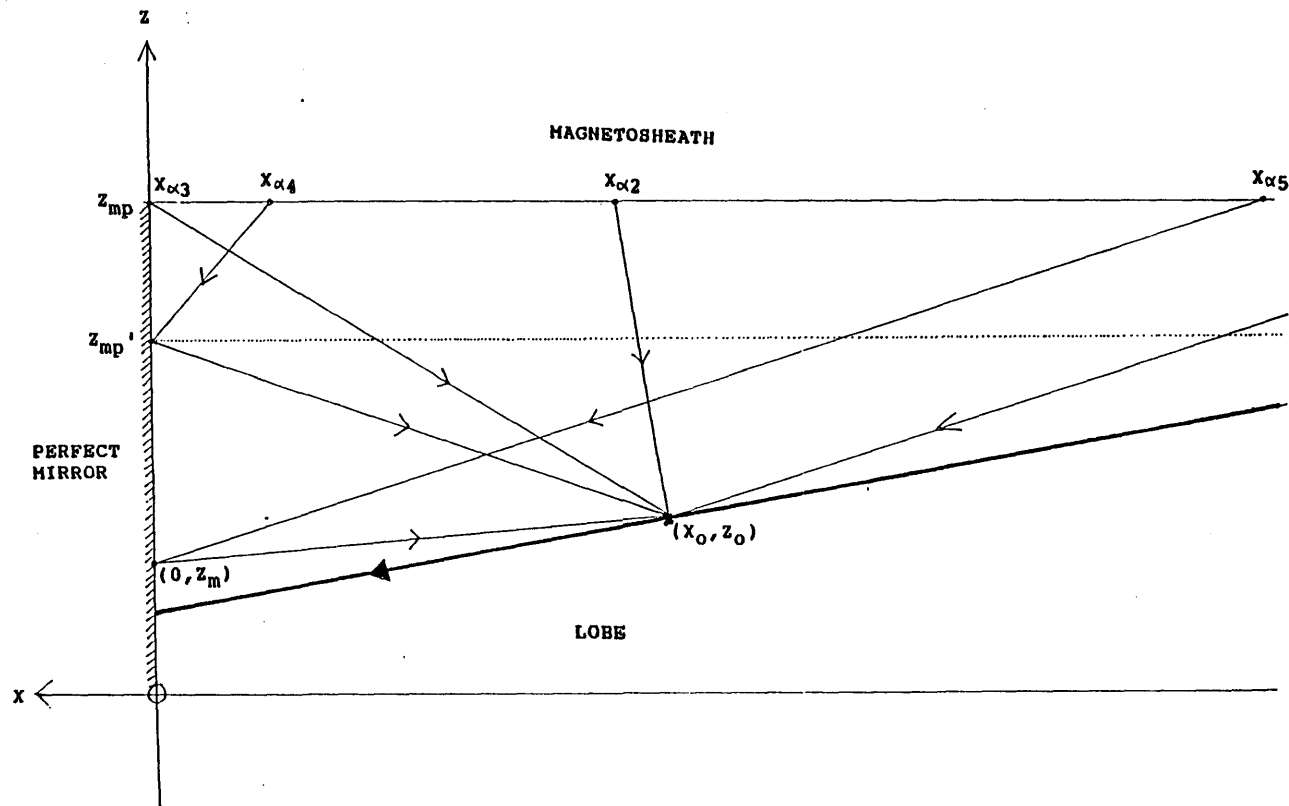


Figure 5.18 Trajectories in a model lobe for a measuring point further from the magnetopause. The format is the same as that in Figure 5.16, except that the relative position of the magnetopause used in that figure is denoted by the dotted line. The 5 trajectories shown are for the same particle pitch angles used in figure 5.16. The points of entry for the field and anti-field aligned particles have moved further downtail, and the limiting pitch angle is now given by a particle whose pitch angle is closer to 90° than the previous case.

particle trajectory thus cuts the new magnetopause location (solid line) at a different x position to the case described above (dotted line). For those pitch angles that are well away from the peak (i.e. those particles which are largely field aligned, or anti-field aligned) the source points are now much further away the Earth - the trajectories cross the magnetopause location at greater negative x -positions than previously. The particles of these pitch angles consequently have lower values of $f(v_{\parallel}, v_{\perp})$ than the case described above. The 90° pitch angle particle has only a small change in its source position, which is negligible in the $\cos \theta = 1$ approximation, such that the value of f for this particle is unchanged. The third trajectory, which represented a pitch angle between 90° and the old limiting pitch angle α_L in the previous case, now enters the lobe at the point $(0, z_{mp})$, and as such represents the new limiting pitch angle. As explained above this particle will now have the peak value of $f(v_{\parallel}, v_{\perp})$, whilst the particle that had the peak value is now a mirroring particle with reduced value of f . The value of pitch angle corresponding to the limiting trajectory is thus slightly decreased towards 90° . This can also be seen directly from equation (5.13). The value of $(z_{mp}' - z_0)$, which is the distance between the measuring point and the magnetopause, is increased, leading to a smaller value of α_L . Note that the peak value of f (now located at a slightly reduced pitch angle) is, to a first approximation, unchanged from the previous case, whilst the values of f at pitch angles away from the peak are depressed. These two effects lead to a more highly peaked distribution function.

These effects of moving to a measuring position further from the tail magnetopause on the pitch angle distribution are illustrated in the second panel of Figure 5.17, for a position $15 R_E$ from the magnetopause (all other parameters remaining the same as the previous panel). The flanks of the distribution at very high and very low pitch angles (field and anti-field aligned particles) are reduced in value of f compared to the first panel (the distribution observed at $5 R_E$ from the magnetopause, described above) whilst the peak is shifted to a position closer to 90° . The distribution is now much more highly peaked than before, such that the omnidirectional flux, which is a function of the area under such a pitch angle distribution plot, is reduced. The front-to-back ratio ($f(0^{\circ})/f(180^{\circ})$) is now approximately unity since, although the distance between their source points is constant, particles of both pitch angle have source points in the region where the sheath fluxes have fallen to close to the background level, N_{sw} . Note that the net downtail flux still exists

since the peak in the distribution is located at a pitch angle above 90° . The remaining two panels of Figure 5.17 illustrate the pitch angle distributions expected at two other distances from the tail magnetopause, namely 1 RE (panel 3), and 25 RE (panel 4). Note that the omnidirectional flux (proportional to the area under the distribution) and the degree of downtail anisotropy (distance of the peak above 90° and size of $f(180^\circ)/f(0^\circ)$) both fall with increasing distance from the magnetopause. This is broadly in line with the observed features of the lobe distribution, and we recall that Figures 5.7 and 5.8 showed a higher omnidirectional flux, and a larger anisotropy shortly after a magnetopause crossing than was observed later when the spacecraft had moved further into the lobes.

We shall now consider the x -dependence of the pitch angle distributions. For particles that have not mirrored, the trajectories relative to the measuring point are exactly the same as the previous case described above. The point of entry for the field aligned particle is a constant distance downtail from the measuring point independent of x (for constant z), and this holds for all particles which have not mirrored. However, the limiting pitch angle between particles which have and have not mirrored moves to larger pitch angles with increasing distance x away from the Earth. This can be seen from equation (5.12), where, dividing top and bottom by x_0 , the denominator becomes smaller with decreasing x_0 (i.e. further from the Earth), leading to higher values of pitch angle for the particles mapping back to the magnetopause at $x = 0$. The peak in the pitch angle distribution consequently moves to higher pitch angles for decreasing x_0 . Those particles which have mirrored remain to be considered in this context. From Figure 5.16 it can be seen that as the measuring point moves tailward ($|x_0|$ increasing) at fixed z_0 the point at which the field aligned particle (180°) encounters the mirror moves closer to the tail centre plane (z_m reduces). This results in the source point of this particle also moving tailward, however the geometry of the system results in this tailward movement being less than that of the measuring point. Since we have already shown the non-mirrored particles have source points a fixed distance from the measuring point for constant z_0 , it follows that the distance between the source points of the 0° pitch angle particle and the 180° particle increases as x_0 moves downtail. Providing the scale length for sheath flux variations is sufficiently large, such that the density at the entry point of the 180° particle is still above the background solar wind level N_{sw} , this results in an increased front to back ratio

$f(0^\circ)/f(180^\circ)$ at the measuring point. However, the source points of most particles move further from the Earth with the measuring point, so that the omnidirectional flux (as represented by the area under the pitch angle distribution) decreases with increasing distance from the Earth. These effects are illustrated in Figure 5.19, for $x_0 = 100 \text{ RE}$, 20 RE , 400 RE and 800 RE (panels 1 to 4 respectively), with $z_0 = 5 \text{ RE}$ in each case. All other parameters are unchanged from those used above, such that the first panel is identical to the first panel of Figure 5.17, which was described in detail above, and which provides a reference distribution. Again, the dotted lines in each panel represent the flux expected if the constant background solar wind flux only is applied along the magnetopause. As the measuring point moves tailward, the peak in the distribution moves further away from 90° . In panel 2, 20 RE from the mirror, the peak is almost at 90° , since the particle originating at $x = 0$ must have a very small field aligned velocity in order to remain so close to the mirror during the time that the field line takes to convect towards the measuring point. The distributions measured further down the tail have peaks at successively higher pitch angles, since the particle originating at $x = 0$ requires a higher field aligned velocity in order to appear at these tailward measuring points. As described above, the points of origin of the 0° and 180° particles move further tailward with the measuring points, such that the value of f for these pitch angles reduces as the measuring point moves tailward, leading to reduced area under each curve, corresponding to a reduced omnidirectional flux. The distribution at 20 RE (panel 2) is almost symmetrical and will not show a significant downtail anisotropy. However, those distributions measured at positions further tailwards, become increasingly asymmetric, and will show a net downtail flow when measured by the EPAS instrument.

The scale length of the variation of fluxes in the magnetosheath and the hardness of the spectrum (the value of Γ) will also have an effect on the pitch angle distribution observed in the lobes. A typical value of the scale length in the magnetosheath is not well known at present due to an insufficient number of observations to separate spatial and temporal variations. So far we have assumed a scale length $L = 100 \text{ RE}$, which gives a variation of several orders of magnitude in the fluxes in the sheath over the expected spread of source points for a distribution observed in the tail lobes. However, due to the uncertainty in the scale length it is instructive to consider the extreme cases that could apply, namely very short scale lengths, and very long scale lengths. The first case, for

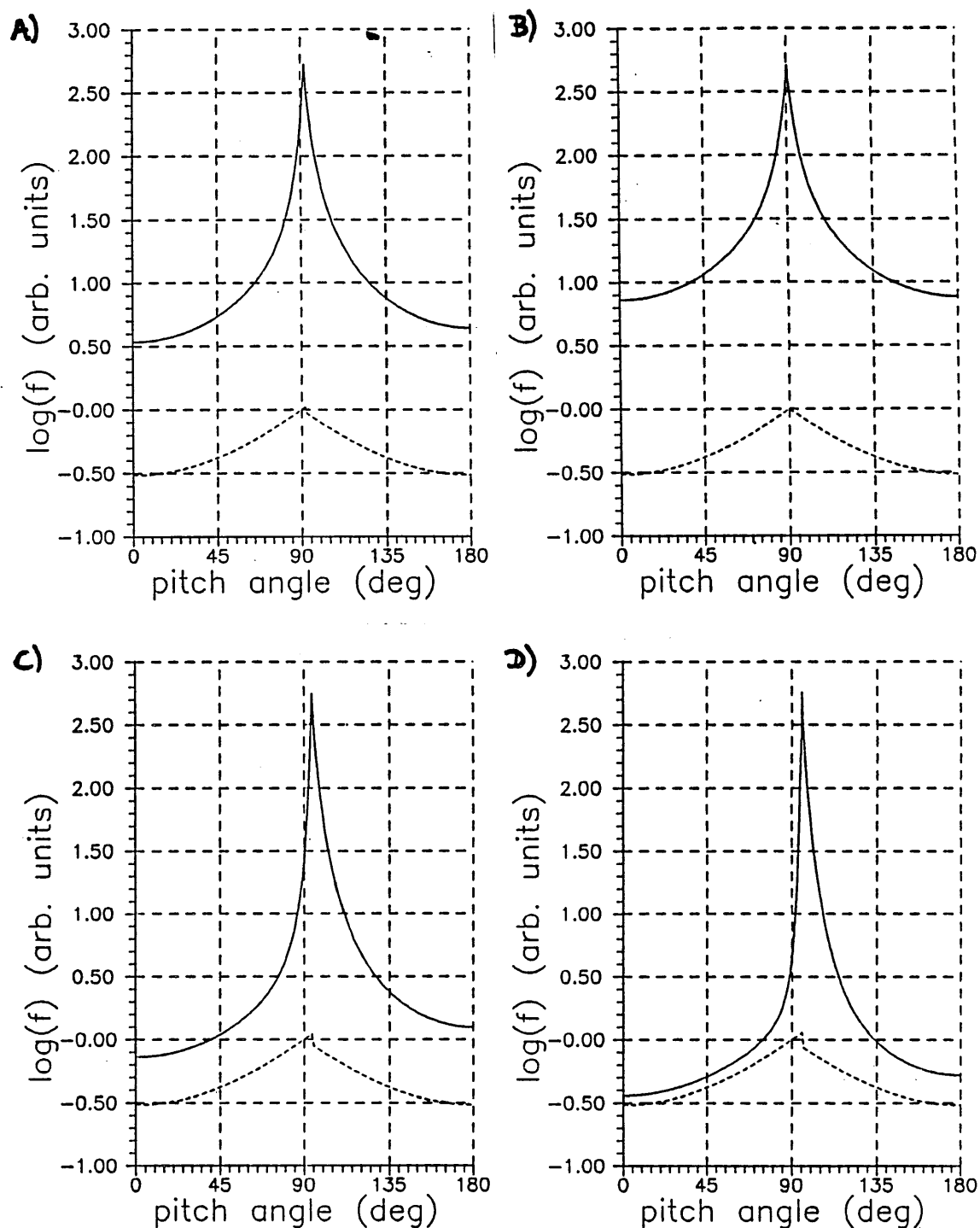


Figure 5.19 Plots of distribution function f against pitch angle for measuring points at various distances downtail, using the same format described previously. The magnetosheath source parameters are the same as those employed in Figure 5.17, and each plot is for a measuring point $5 R_E$ from the magnetopause. Plot (A) is for $100 R_E$ downtail from the perfect mirror, and is the reference distribution used above. The remaining panels are for distances of (B) $25 R_E$, (C) $400 R_E$ and (D) $800 R_E$ downtail. The peak in the distribution is located closest to 90° for positions close to the perfect mirror, and the omnidirectional flux (area under each curve) is greatest at these points. However, the downtail anisotropy increases with distance from the perfect mirror.

a short scale length is illustrated in figure 5.20. The parameters used in each of these panels are identical to those used in figure 5.17, with the exception of the scale length which has been reduced by an order of magnitude, to $L=10 R_E$. The trajectories, source points and entry velocities of particles within the lobe are unaltered from the original case discussed above, so that differences between the two figures arise solely from the variation in the source scale length. Consequently the peaks in the distribution are at the same pitch angles, and have the same values of f . Those particles with pitch angles away from the peak have a much reduced value of $f(v_{||}, v_{\perp})$ and since the sheath fluxes fall to the background level N_{sw} much faster than before (i.e. the sheath flux becomes approximately constant at N_{sw} after a fairly short distance downtail) the variation of $f(v_{||}, v_{\perp})$ for these pitch angles depends only on their entry velocity, giving a slow variation, and little difference between field aligned and anti-field aligned particles. However those particles originating very close to the Earth have a highly enhanced f -value such that the pitch angle distribution rises to a very sharp peak about the limiting pitch angle, as can be seen in each panel of Figure 5.20.

The second case, of very long scale lengths, is important in its own right when we consider solar particle events. As explained in the data section (Section 3) of this chapter, the fluxes in the solar wind increase by several orders of magnitude during such periods, and will be much higher than those fluxes which are produced by the solar wind -magnetosphere interaction. Under these circumstances the value of N_{sw} far exceeds the value of N_0 , such that the latter is negligible compared to the former, and can be neglected in our analysis, resulting in a constant flux (or an infinite scale length of variation) along the magnetopause in this case. At the same time the energy spectra of particle fluxes during these events becomes much harder, such that Γ may at times be less than unity (i.e. the fluxes of more energetic particles are much enhanced relative to the lower energy particles). Although the trajectories of the particles within the model lobe, and consequently the source points and entry velocities, remain the same as above, the dependence of $f(v_{||}, v_{\perp})$ on these quantities is now much reduced, as can be seen in the pitch angle distributions shown in figure 5.21. Again the same parameters as Figure 5.17 are used, but we now assume an infinite scale length, and reduce the value of Γ to 1.5. Since there is no spatial dependence in these pitch angle distributions, the peaks are produced by the variation of entry velocity (i.e. variation of velocity in the field line rest

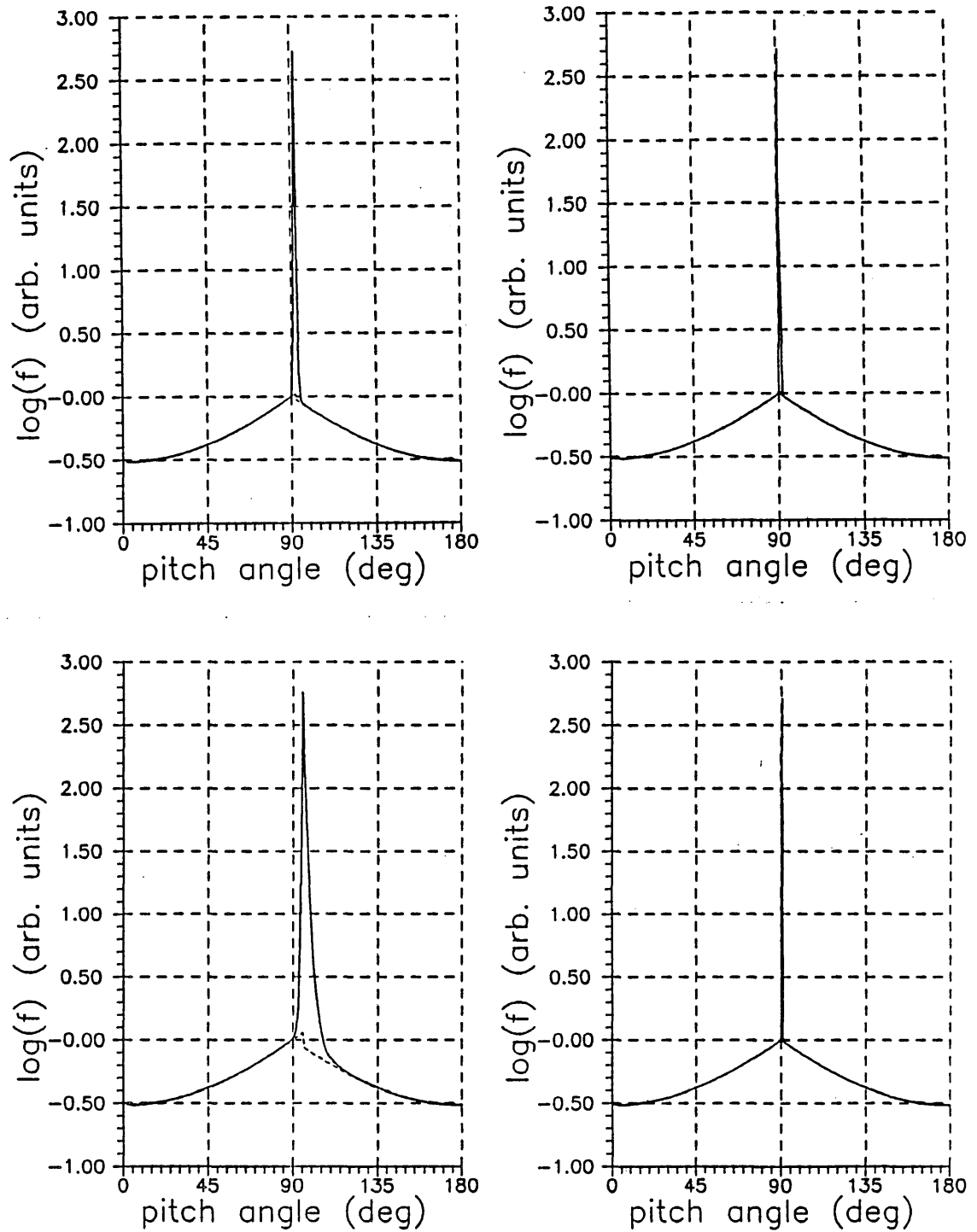


Figure 5.20 Plots of distribution function f against pitch angle for very short scale lengths for the magnetosheath source strength. The parameters used in each of the plots are identical to the corresponding plots in Figure 5.17, except that the scale length has been reduced to 10 R_E . The enhancement in sheath density is confined to the near Earth region, so that only particles entering the lobes at these points have enhanced values of f , resulting in distribution functions that have extremely sharp peaks.

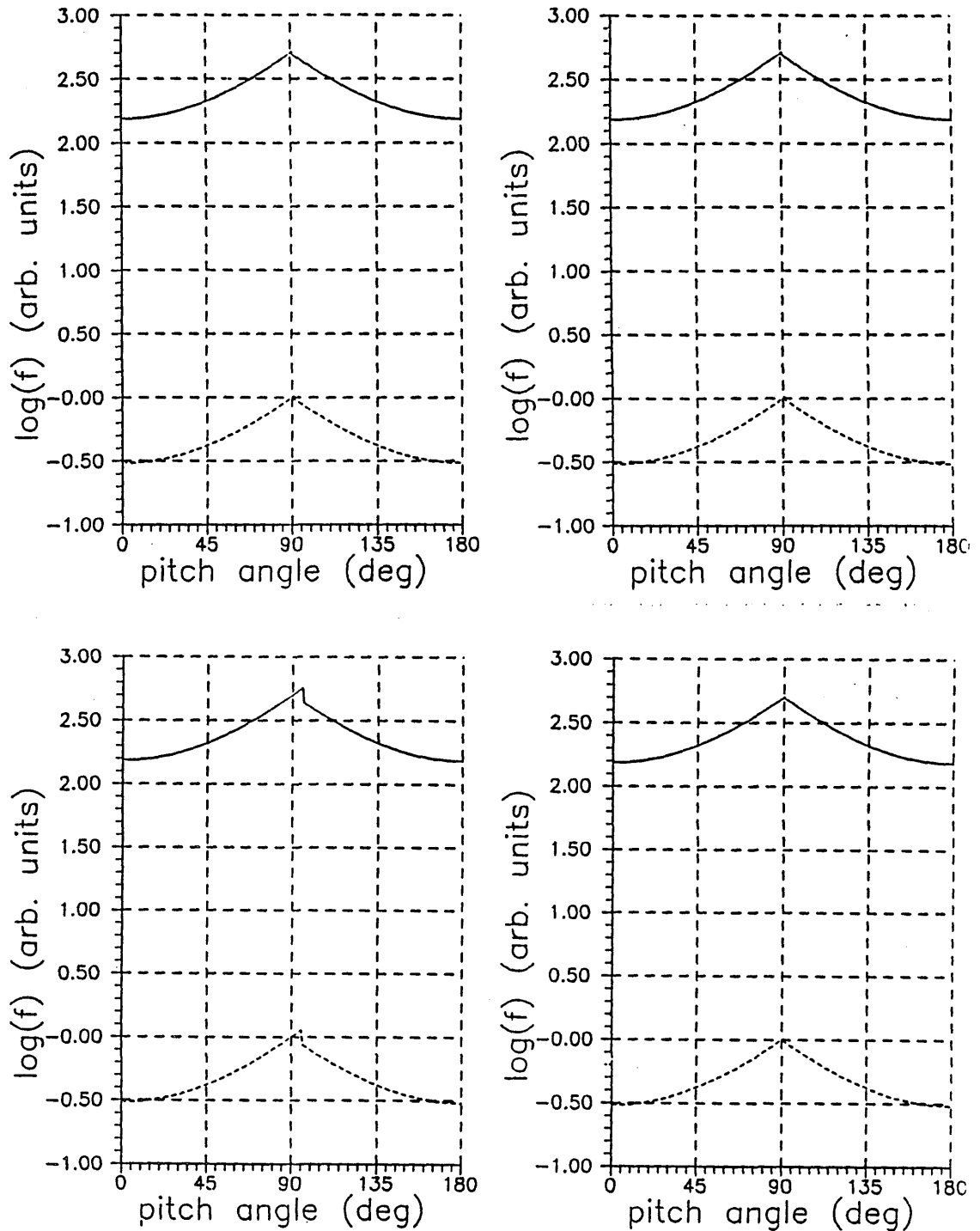


Figure 5.21 Plots of distribution function f against pitch angle for very long scale lengths for the magnetosheath source strength. The parameters used in each of the plots are identical to the corresponding plots in Figure 5.17, except that the scale length is now infinite, so that the enhanced sheath fluxes are now found along the entire length of the magnetopause. This situation is analogous to that which occurs during solar particle events. The distributions found in the lobe have very broad peaks, resulting in little anisotropy, and very high omnidirectional fluxes, as are observed during solar particle events.

frame, see Figure 5.14 and associated discussion). This has a relatively smaller effect than previously since the value of Γ is reduced, and so produces only a small and broad peak in the distributions. There is a discontinuity in the distributions at the peak, since the parallel components of the entry velocities reverse for particles on either side of the limiting trajectory which maps to the magnetopause at $x = 0$. This is seen most clearly in panel 3, which has the largest $v_{\parallel}$ at the peak, and consequently has the largest discontinuity. Note that, with the exception of the position of the peak, the z -dependence (and x -dependence, not shown) of the distributions is lost, such that the omnidirectional flux (proportional to the area under the distribution) is approximately constant within the tail lobe. However, the omnidirectional flux will, of course, be much larger in magnitude than the previous cases considered, as the source fluxes during solar particle events are much larger. The downtail anisotropy is small, given only by the peak being located at pitch angles slightly larger than 90° , and thus becomes smaller with increasing distance from the magnetopause. Since the values of $f(v_{\parallel}, v_{\perp})$ shown in Figure 5.2.1 have a much smaller variation with pitch angle than the cases considered previously, these plots correspond to quasi-circular EPAS sector plots, as are observed during solar particle events. The model is thus capable of reproducing the form of the data that are observed in the deep tail during such solar particle events.

In summary of this section, we have shown how a very simple model lobe with a perfect mirror at its Earthward end can reproduce, semi-quantitatively, those properties of the lobe energetic ion pitch angle distributions observed by ISEE-3, both under normal, and solar particle event conditions. The model produces pitch angle distributions which are highly peaked close to 90° with a small downtail anisotropy under normal conditions, when a dominant, near-Earth source is present. Under solar particle conditions the variation in f is much smaller, such that the EPAS instrument on the spacecraft would observe more isotropic distributions.

The model, by its very simplicity, obviously makes several assumptions which are quite large departures from reality. In the next section we shall discuss in greater detail the most severe of these assumptions, and how relaxing them would affect our model pitch angle distributions.

6. Motion of Particles in a Model Lobe with Increasing Field Strength Close to the Earth.

In the last section the basic properties of the particle motion in a simple, uniform field lobe model were discussed in order to determine the points at which particles of particular pitch angles enter the lobes. The only complications to tracking the motion arise from particles interacting with the perfect mirror. Since this simply reverses the x-component of the particles velocity at the position $x = 0$, simple equations for the points of entry for each particle were obtained. However, this field configuration, whilst representing the distant tail quite faithfully, is, at first sight, a gross over simplification to the field in the near Earth tail ($x > -100 R_E$). As the distance from the Earth increases the observed field strength in the tail drops, rapidly at first, but then more slowly, settling to an approximately constant value of 8 - 12 nT at distances beyond 100 - 200 R_E downtail (Slavin et al, 1985). This is largely due to the flaring of the tail which results from the balance between the solar wind ram pressure and the magnetic pressure of the lobe flux tubes, as discussed by Coroniti and Kennel (1972). Consequently, in order to make our model lobe more realistic, we need to replace the perfect mirror at $x = 0$ with some field strength increase in the near Earth region ($x > -100 R_E$). The motion of particles at distances greater than $-100 R_E$ is unchanged from that described in the last section, but the motion closer to the Earth will be substantially altered, with particles of different pitch angles mirroring at different positions within the near-Earth region. In the rest of this section we shall discuss this motion, and the effect on the pitch angle distributions that we predict in the lobes, in more detail.

The exact variation of the field strength in the near-Earth tail is a complicated function of distance. A full treatment is inappropriate here, since we wish only to investigate any major departures that some field strength increase in the near-Earth region has on the results from the simple model described above. We shall model the effect by retaining our perfect mirror at $x = 0$, but including a gentle slope in the field strength between 0 and $-100 R_E$. The field strength variation assumed is shown as a function of distance in Figure 5.22. The field strength at distances greater than 100 R_E downtail is a constant 10 nT, and we shall assume that the x- and z-components of the field are the same as those employed in the last section (i.e. $B_x = 10$ nT, $B_z = -0.15$ nT). Between 0 and $-100 R_E$ we assume a linear ramp in the field strength, with a gradient such that

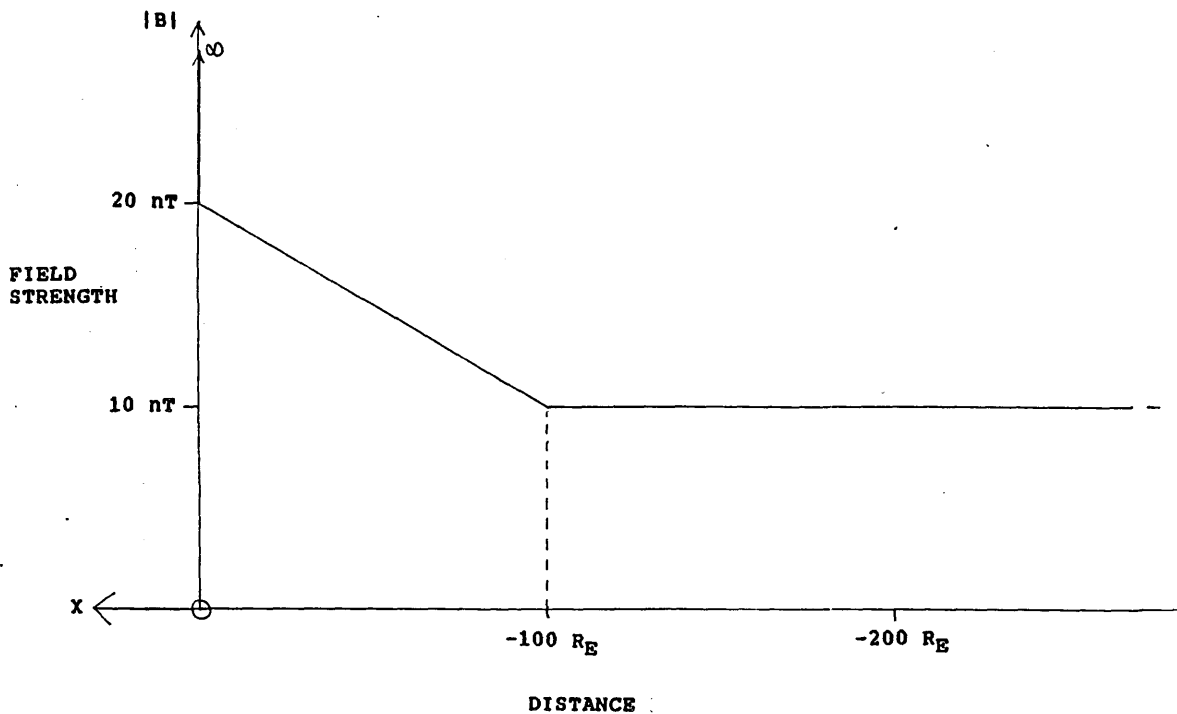


Figure 5.22 The variation of field strength with distance down the tail assumed in the revised lobe model. The field is unaltered for distances greater than $100 R_E$ downtail, and we retain the perfect mirror at $x = 0$. Between these two points the field is assumed to rise linearly from 10 nT at $x = -100 R_E$ to 20 nT shortly before the perfect mirror. This field variation therefore includes the effect of the observed near-Earth increase in the lobe field strength.

the field strength doubles across this region, reaching 20 nT at $x = 0$, where we apply our perfect mirror (i.e. infinite field strength), as before. The field strength in the near Earth region ($0 > x > -100 R_E$) is thus (recalling values of x in the lobe are all negative)

$$B(x) = 20 + x/10 R_E \quad (\text{nT}) \quad . \quad (5.16)$$

We wish to employ the same technique for determining the source points of the lobe energetic particles as we did in the last section. For this we need to know explicitly where the field line at the measuring point (x_0, z_0) threads through the tail magnetopause (cf. equation (5.8)). An exact field structure within the ramp region needs to be assumed for measuring points with $x_0 > -100 R_E$, in order to identify the points at which each field line intersects the magnetopause. However, for source points further downtail the field line/magnetopause interaction point can be calculated in exactly the same way as before. For this reason, we shall confine ourselves to studying the source points for particles measured in the deeper tail, such that the near Earth field does not need to be explicitly defined. Assuming that the field line is dragged tailward with the sheath flow at a constant speed $-v_{sw}$ along the entire length of the tail, the field line located at (x_0, z_0) (where $x_0 < -100 R_E$) at $t = 0$ cuts the magnetopause at positions given by equation (5.9) at any other time t , as described in the last section. It therefore suffices to redefine the x -component of the velocity of each particle to include the effects of the linear increase in field strength Earthward of $-100 R_E$ in order to locate its source point, using the same technique as the last section. Again particles fall into distinct types - those which have no part of their trajectory in the increasing field strength region, those which reverse their velocity in this region, and those which hit the perfect mirror. The new trajectories are illustrated in figure 5.23, in the same format employed previously, but including a separate region close to the Earth where the field strength is increasing. Obviously, those particles that do not enter the mirror region behave in exactly the same way as described in the last section, as they move in exactly the same field configuration as before, and therefore cross the magnetopause at the same positions $x_{\alpha 1,2,3}$. The value of f associated with these particles is also unchanged. These particles are bounded by the trajectory of the particle which enters the lobe at $x = -100 R_E$ and then moves tailward to the point (x_0, z_0) . The pitch angle of this particle can be obtained in an analogous way to the limiting pitch angle particle in the last section. Putting

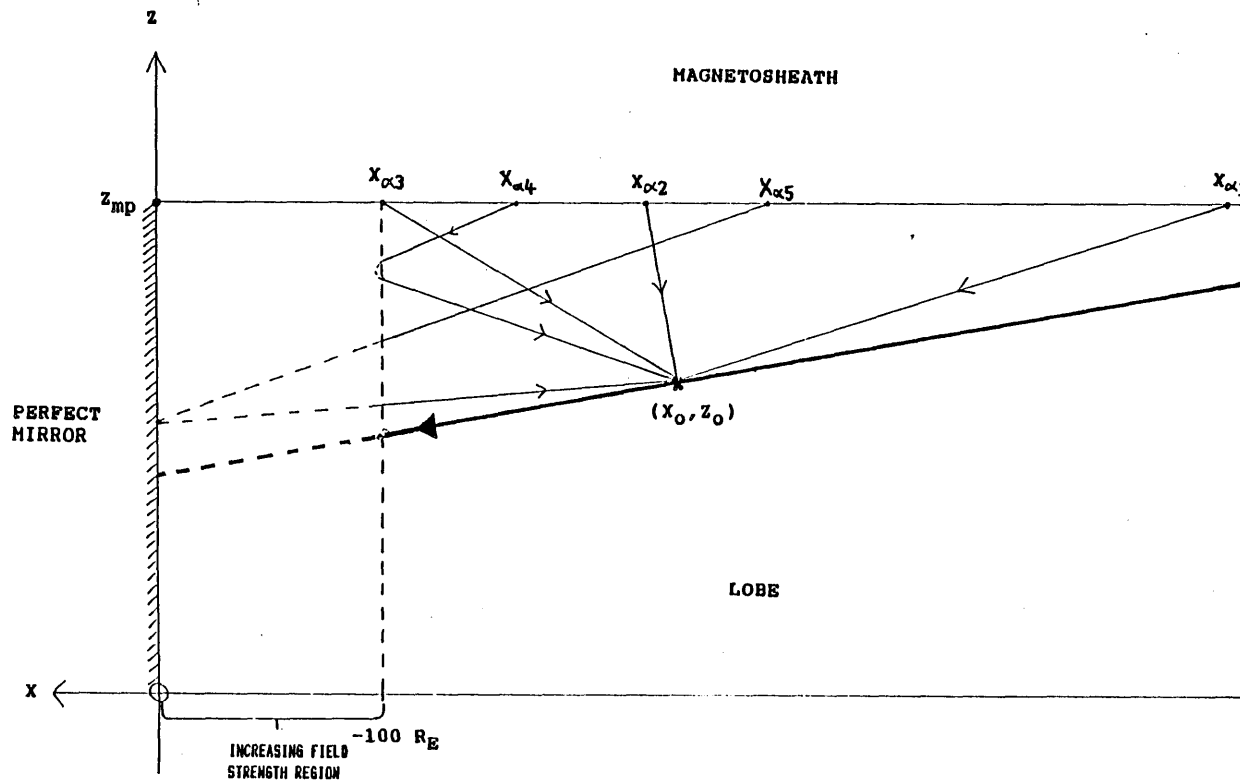


Figure 5.23 Particle trajectories in the revised model lobe. The format employed is the same as that employed previously, except that we now include a region of increasing field strength close to the Earth. The trajectories shown are for the same pitch angles used in Figure 5.16. The limiting pitch angle between unmirrored particles and those which have undergone mirroring within the near-Earth region or at the perfect mirror is given by that particle entering the lobe at $x_{\alpha 3}$. The unmirrored particles have the same trajectories as in the previous model. Particles with pitch angles slightly above the limiting pitch angle are quickly mirrored, and have source points tailward of $-100 R_E$. Those which are mirrored at the perfect mirror spend a short time in the near-Earth region, and also have source points tailward of $-100 R_E$. The particle entering at $x_{\alpha 3}$ therefore represents the peak in the resulting distribution in this case.

$x_f(t) = x_p(t) = -100 R_E$ in equations (5.9) and (5.10) respectively and then eliminating t , this pitch angle is given by

$$\alpha_L' = \cos^{-1} \left[\frac{-v_{sw}(100 R_E + x_0) \sqrt{(m_i/2E)}}{((100 R_E + x_0) - (z_{mp} - z_0) \cdot B_x/|B_z|)} \right]. \quad (5.17)$$

which again gives a pitch angle a few degrees above 90° , depending on position in the lobe, and is represented in Figure 5.23 by the trajectory crossing the magnetopause at $x_{\alpha 3}$. All particles with pitch angles above this value must have spent some part of their trajectories within the near Earth region, where their motion is either reversed by gradual deceleration in the field strength ramp, or by the interaction with the perfect mirror at $x = 0$. We shall now study the motion of these particles in detail.

The increase in magnetic field strength required to reverse the field aligned motion of a gyrating particle can be obtained from the conservation of magnetic moment μ . This holds provided the field strength as 'seen' by the particles varies slowly in time. In the field assumed here this breaks down at $0 R_E$, where the field strength suddenly becomes infinite. However, in reality the field strength varies more slowly in the lobes, so we shall invoke conservation of μ at all points within our model lobe. Note also that we shall ignore gradient-B and curvature-B drifts which are also negligible in the real lobe. For a particle detected at some point (x_0, z_0) in the lobe, with pitch angle α_0 , the magnetic moment is given by

$$\mu = E \cdot \sin^2 \alpha_0 / B(x_0), \quad (5.18)$$

where E is the energy of the particle, and $B(x_0)$ is the field strength at the measuring point. When the particles enter a region of increasing field strength, their pitch angle moves closer to 90° , such that they eventually mirror and their motion is reversed. The field strength at the mirror point x_m (i.e. where the particle pitch angle is 90°) is thus given by

$$B(x_m) = B(x_0) / \sin^2 \alpha_0. \quad (5.19)$$

For measuring points outside of the near-Earth region $B(x_0) = 10$ nT, whilst the maximum field strength before the perfect mirror is encountered is 20 nT. It therefore follows that, in this case, all particles appearing at (x_0, z_0) with pitch

angles between the limiting pitch angle and 135° have some part of their trajectory in the near earth region, but have not hit the perfect mirror, whilst those with pitch angles above 135° must have interacted with the perfect mirror. The exception to this is particles that may have their source points within the near-Earth region, but these represent a special case which we shall deal with separately later. Note that those particles with pitch angles close to the limiting pitch angle (i.e. those closest to 90° , such that $\sin^2 \alpha_0$ is close to unity) need only a small increase in field strength to cause mirroring, and consequently these particles do not penetrate very far into the near earth region before having their motion reversed. This is illustrated schematically in figure 5.23 by the trajectory which crosses the magnetopause at position $x_{\alpha 4}$. The trajectory is quickly reversed in the increasing field strength region, and the particle re-emerges after a very short time. Note, however, that this trajectory is associated with the same pitch angle of the particle that originated at $x = 0$ in the simpler model of the last section, and as such represented the peak in the pitch angle distribution. The source point for this particle is now tailwards of $-100 R_E$, and it enters the lobe with an Earthward motion. This particle thus has a reduced value of $f(v_{||}, v_{\perp})$, which no longer represents the peak in the pitch angle distribution.

For particles which have very large pitch angles the increase in the field strength between $x = -100 R_E$ and $x = 0$ is insufficient to reverse their motion, and so they hit the perfect mirror. The trajectory of such a particle is illustrated in figure 5.23 by the trajectory crossing the magnetopause at position $x_{\alpha 5}$. Note that the portions of the latter two trajectories and the field line within the near Earth region are shown dashed since the exact form of these quantities is not explicitly defined in this region.

The parts of the pitch angle distribution made up by particles of the various types of trajectory are illustrated in Figure 5.24. This shows a plot of $v_{||}$ against $v_{\perp}$ divided into sectors, according to which type of trajectory the particles of these velocities have undertaken. Those particles whose velocities fall into the sector marked "A" are those which are moving Earthwards, and are yet to mirror. Those in the other three sectors have all moved into the near-Earth mirror region at some point prior to their arrival at the measuring point; those in sector "B", with pitch angles above 135° have interacted with the perfect mirror, whilst those in sector "C" have had their motion reversed in the field ramp. The remaining sector, "D", contains those particles which may

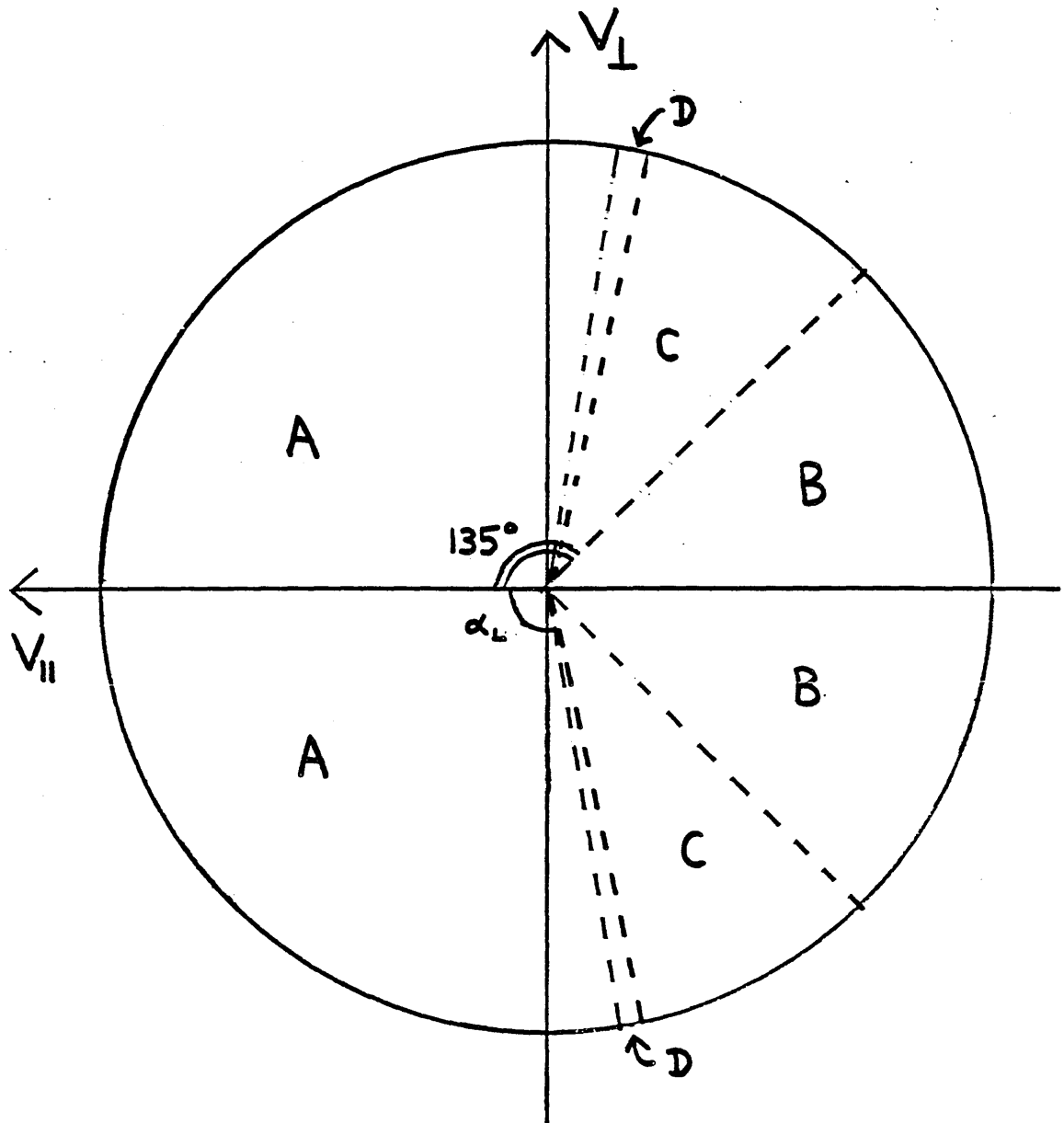


Figure 5.24 Diagram indicating the type of trajectory that particles of each pitch angle have undergone to reach the measuring point. those particles whose velocity components fall within the sector marked a are the unmirrored particles, bounded by the pitch angle α_L . Particles with pitch angles above 135° (those with velocity components in sector B) have had their motion reversed at the perfect mirror, whilst those in sector C have mirrored within the near-Earth field increase. All of these types of particles have source points tailward of $-100 R_E$. The remaining sector (sector D) represents those particles which may have entry points within the near-Earth region, which are not covered by our theory. In practise the size of this sector is extremely small providing the measuring point is not close to both the Near-Earth region and the magnetopause.

have their source points within the near-Earth region, and are a special case that will be discussed fully below.

We shall now discuss the form of the ion trajectories in this model lobe in more detail. The source points for particles that enter the near Earth region in this model (sectors "B" and "C" in Figure 5.24) can be calculated by considering the acceleration of particles in this region. The apparent force acting on the particles which reduces their field aligned (taken again to be approximately the x-direction) component of velocity is given by

$$F_x = -\mu \frac{dB(x)}{dx} . \quad (5.20)$$

Since we have assumed a linear field increase in this region, the force on each particle is constant and depends only on the particles pitch angle at the measuring point, i.e. (from equations (5.16),(5.18),(5.20))

$$F_x = -\mu / 10 R_E , \quad (5.21)$$

and consequently the field aligned acceleration of each particle is constant within the mirror region. The position x_m at which each particle mirrors (i.e. the point at which its field aligned motion reverses) may also be deduced from equations (5.16) and (5.19),

$$x_m = -100.[2 - 1/\sin^2 \alpha_0] \quad (R_E) \quad (5.22)$$

for particles that do not hit the perfect mirror ($\alpha_0 < 135^\circ$, sector "C"), whilst $x_m = 0 R_E$ for all other mirrored particles. The time t_m taken for the particle to move from the edge of the mirror region to the actual mirror point is then a solution to the equation

$$(x_m + 100 R_E) = v_{||} t_m - (F_x/2m_i).t_m^2 \quad (5.23)$$

Since the acceleration is constant, t_m represents half the total time the particle spends in the near earth region. In addition to this the particle takes a time

$$t_1 = (x_0 - 100 R_E)/v_{||} \quad (5.24)$$

to move from the mirror region to the measuring point where it is located at $t = 0$. The particle thus first *entered* the near earth region at a time $t_e = -(2.t_m + t_1)$. Equation (5.9) can be used to locate the intersection of the field line, on which the particle is located, with the magnetopause at this time. Provided this point is further downtail than $-100 R_E$, the particle has a source point in the distant tail, which, using the values of t_e , $x_f(t_e)$, and the fact that the particle is located at $x = -100 R_E$, and has speed $v_{||}$, can then be calculated explicitly using the methods employed in Section (f). The possibility that $x_f(t_e) > -100 R_E$, such that the particle has a source point within the near Earth region will be discussed at the end of this section.

The value of $f(v_{||}, v_{\perp})$ for both these types of particle (i.e. those mirrored in the near Earth region and those mirrored at the perfect mirror) can thus be deduced from these source points and by noting that, since they have all had their motion reversed at some point within the near Earth region, the entry velocity $v_{||}$ is the subsequently measured velocity reversed in sign.

The theory so far described in this section covers all particles that are both detected and have their source points in the distant lobes of this model (i.e. all the particles whose velocity components fall in sectors "A", "B", and "C" of Figure 5.24). As described above we will not consider measuring points within the near Earth region, however it is possible that some particles detected in the distant lobe have their source points in this region (sector "D" of Figure 5.24). If, at the time t_e , when the particle is located at $x = -100 R_E$, the field line intersects the magnetopause at a point closer to the Earth, (such that the field line is located entirely within the near Earth region) it follows that the particle must be located in the magnetosheath, and therefore must enter the lobe at some time $t_e + dt_e$, at some position within the near-Earth region.

However, we note that for particles with field aligned velocities which are large compared to the sheath flow speed v_{sw} , the time spent in this region is small compared to the time it takes for a field line to move a significant distance, so that the field line/magnetopause interaction point must be located just tailward of $x = -100 R_E$ at $t = 0$ in order for these particles to originate in the near Earth region. Hence particles of this type detected at (x_0, z_0) only have sources within the near Earth region for x_0 very close to $-100 R_E$ and z_0 very close to the magnetopause location z_{mp} , i.e. a very restricted region of the lobe in this model.

Those particles with field aligned speeds comparable to the sheath flow speed (i.e. those within a few degrees of the limiting pitch angle described by equation (5.17)) may also have sources within the near Earth region. However the distance they may penetrate into this region is very small since they mirror at a field strength only slightly higher than that found in the deep tail. Hence their point of entry into the lobe must also be within a few Earth radii of $x = -100 R_E$. These particles may be observed at a general measuring point within the lobe (unlike the "fast" particles with sources in this region which can only be detected at positions close to the magnetopause and close to $-100 R_E$). However, the trajectory of these particles to the measuring point is very close to that of the limiting pitch angle particle, which crosses the magnetopause at $x = -100 R_E$. The field aligned velocity of these particles within the constant field section of the lobe must therefore be very close to that of the limiting pitch angle particle, such that the velocity components of these "near-Earth" particles occupy a small section (section "D") in Figure 5.24, just above the limiting pitch angle. In addition, the particles are accelerated within the near-Earth region, and may have had their direction of motion reversed, such that although they are detected with a larger tailward field aligned speed than that of the limiting pitch angle particle, they entered the lobe with a speed that is of order than, or less than, that of the limiting particle. It is therefore likely that any increase in the value of f for these particles above the value of $f(\alpha_L)$ due to their source point being slightly closer to the Earth, will be more than cancelled by a decrease in f due to the entry velocity being less tailward than that of the limiting pitch angle particle. The exact balance of these two effects depends on the exact nature of the assumed magnetosheath flux variation, but the result is that the value of $f(v_{||}, v_{\perp})$ for the limiting pitch angle particle is, to a very close approximation, the maximum value of f observed at that measuring point. Since the source point for this new maximum is further tailwards than that for the constant field strength lobe model of the last section, we expect the peak produced by this new model to be smaller.

It should be noted that although the motion of particles described in the last few paragraphs is complicated, and not easy to comprehend, they represent a very small fraction (less than 1°) of the total range of pitch angles (as represented by figure 5.24, for example) at a "typical" measuring point. This is evidenced by the fact that when making calculations of the source points, it is

possible to find no particles with source points within the near-Earth region, even if the calculations are made at 1° intervals.

Figure 5.25 shows the pitch angle plots obtained using the model lobe described in the last section (dotted line) and by using this revised model (solid line) with the same input parameters ($x_0 = -150 R_E$, $z_{mp}-z_0 = 10 R_E$, $L = 100 R_E$). The dashed lines again show the distribution expected with no enhancement of flux above the solar wind levels. Since the particles around the peak in the first model have source positions much further down the tail those in the second model, the peak represented by the solid line is shifted slightly, and is not as high. The low pitch angle particles ($\alpha < \alpha_L'$) have exactly the same form as before, whilst the very high pitch angle particles (those above 150°) are not significantly altered as the near Earth acceleration results in only a small change in their velocities in this region. Particles with pitch angles between 120° and 150° are slightly enhanced as their source points are closer to the Earth due to the fact that they are significantly slowed in the near-Earth region, whilst the field line speed is unaltered.

The results presented in this section show that the qualitative form of the pitch angle distribution is not significantly altered by the inclusion of a near Earth ramp in the field strength. We have therefore shown in this section that the results presented in the last section show all the essential features of the observed distribution, despite the simplicity of the model assumed. The exact form of the pitch angle distribution in the lobe does depend on the exact form of the field strength variation in the near Earth region, but we have shown that the general form is unaffected. The peak in the distribution, and the asymmetries within it are constant features of the distribution, which are altered in detail only by varying the field within near Earth region of the model lobe. The major considerations in predicting the form of the pitch angle distribution in the lobes are thus just the variation of the source distribution in the sheath and the mechanism for entry of the particles in the to the lobes, as discussed in previous sections.

7. Summary.

In this chapter we have considered, from both an observational and theoretical viewpoint, the form of the distributions of energetic ions ($E \geq 35 \text{ keV}$) in the

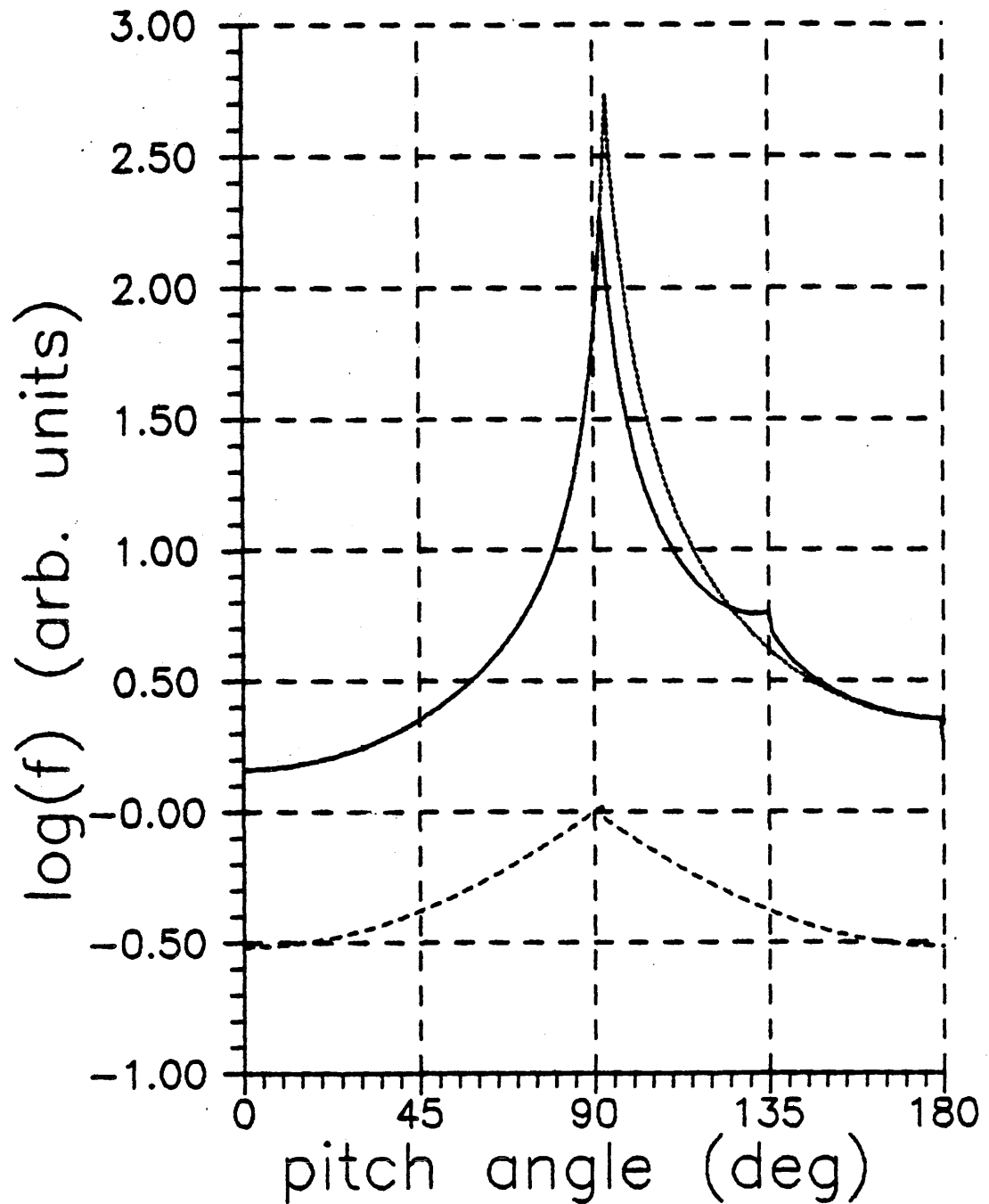


Figure 5.25 Distribution function f versus pitch angle for the simple and revised model lobe, for a measuring point 150 R_E downtail from the Earth and 10 R_E from the magnetopause. The sheath source parameters are the same as those employed in Figure 5.17, and the dashed line again represents the distribution expected if no near-Earth enhancement of the source flux was present. The solid line represents the distribution obtained from the revised model, the dotted line that from the simple model. Although there are differences in detail between the two distributions, they both show the same qualitative behaviour expected for the tail lobe. This figure illustrates that the simple model lobe is adequate to explain the observed energetic ion distributions in the tail lobes.

lobes of the deep geomagnetic tail, and as a result we have managed to produce a model which explains the main features of the observations.

As explained in the introduction, there has been very little work done in this area in the past, since most work on the tail has concentrated on the plasma sheet and associated phenomena. In this chapter we have therefore briefly reviewed the characteristics of the lobe energetic ions, as observed by the EPAS instrument on board ISEE-3. These showed that during "normal" times the lobe pitch angle distribution is highly peaked at pitch angles closely perpendicular to the magnetic field direction, which points either directly towards or away from the Earth in the lobes. The distributions also show a small downtail anisotropy, which becomes larger when the spacecraft is close to the magnetopause. The omnidirectional flux is also largest close to the magnetopause, and falls with increasing distance from it. During periods of solar particle enhancements however, the lobe distributions become much more closely isotropic, such that the EPAS instrument sees approximately equal counts in each look direction.

We have proposed a model which successfully reproduces these observed features of the data. In this model, a spatial variation of the magnetosheath energetic ions, which act as the source population for the lobes, exists along the length of the tail, with enhanced fluxes at the Earthward end gradually falling to the solar wind background level some distance down the tail. This enhancement is due to either production of ions at the bow shock, and/or escape of ions across the dayside magnetopause from the near-Earth ring current. Diffusion of ions in the turbulent magnetosheath field creates distributions which are isotropic in the solar wind rest frame. In our model we have assumed that these ions may gain entry to the lobes across a magnetically open magnetopause. Consideration of the motion of the particles within a simple model lobe, in which the field strength is constant everywhere but at the Earthward end, where we apply a perfect mirror, allows the determination of the points at which particles of each pitch angle reaching a specified measuring point crossed the magnetopause. The relative value of $f(v_{\parallel}, v_{\perp})$ associated with that pitch angle can then be determined from the source strength at the point of entry and from considerations of the physics of the particle/magnetopause interaction by assuming that the value of f is conserved along the particles trajectory from the magnetopause. The resulting theoretically produced pitch angle plots also show a peak in the distribution at a few degrees above 90° to

the field direction, and an anisotropy, in which particles moving tailwards have generally higher values of $f(v_{\parallel}, v_{\perp})$ than those moving Earthwards.

The spatial variation of these distributions within the lobe was then studied. In concordance with the observations we find that the omnidirectional flux (as represented by the area under the f versus pitch angle curve) and the degree of anisotropy both increase as the measuring point moves further from the magnetopause. We also find that the degree of anisotropy increases with distance down the tail, although in this case there is a decrease in the omnidirectional flux.

The major effect on the pitch angle distributions, however, is the scale length of the source flux variation in the magnetosheath. For very small scale lengths the distributions are peaked sharply at the maximum, whilst for very long scale lengths the distribution is broader, and is more closely isotropic. The latter case explains the observations made during solar particle events, when the spatially varying flux in the sheath is negligible compared to the high background fluxes existing in the solar wind, when the scale length effectively becomes infinite.

Finally, we have refined our lobe model to include a (more realistic) field increase in the near-Earth region. Although the detail of the results differed from those produced by the simple model, the qualitative variation between the models is small, and we conclude that our simple model is thus sufficient to explain the main features of the energetic particle populations observed within the tail lobes.

CHAPTER 6.

SUMMARY AND SUGGESTIONS FOR FURTHER WORK.

In this thesis we have studied a number of aspects of charged particle behaviour in the geomagnetic tail, from both observational and theoretical points of view. In the introductory chapter we briefly described the formation of the magnetotail, and plasma and field structures observed within it. The currently accepted theories of current sheet stress balance and their role in the formation of the plasma sheet were reviewed, and the neutral line model of substorms was also described. This latter is currently the most successful model of tail dynamics during periods of enhanced geomagnetic activity, and provides a useful framework by which both Earth-based and spacecraft observations may be related. The purpose of this chapter is to provide a summary of the work presented in this thesis, and to place it in context next to the work that has previously been done in this field. However, some of the work presented in the preceding chapters still has scope for expansion and refinement, and much of it has potential applications that may aid our understanding of magnetospheric processes. This chapter is therefore also devoted to suggestions for further work, both in terms of improvements to the work itself, and for future applications.

Two chapters of this thesis considered the behaviour of the time dependent tail. In Chapter 2, we showed how existing steady-state models of magnetic reconnection based on local 1-D stress balance conditions could be generalized to include the effects of time-varying reconnection rates, and of motion of the neutral line. Providing that the reconnection rate and the neutral line speed do not become too large (such that the component of the field threading the current sheet remains small compared to the transverse component), the principles of 1-D stress balance hold in the regions of the current sheet away from the neutral line itself. Under these circumstances the calculation of the thicknesses of the reconnection-associated field and particle layers is straightforward, using the principle of flux conservation in the reconnected field wedge. Results from this study showed that increases in the reconnection rate lead to an enhanced component of the field (B_z) threading the current sheet and thicker field and particle layers on both sides of the neutral line. Neutral line motion results in the compression of the field ahead of the neutral line, giving thicker field and particle layers and increased B_z , and a rarefied field behind, with thinner layers and decreased B_z . Apart from the assumption of one-dimensionality, the only limitation of the theory is the assumption of a cold beam of plasma in the outflow from the current sheet. The theory therefore takes no account of

heating of plasma within the current sheet. In principle this could be included, but at the expense of the simplicity and tractability of the theory, and the results would not be expected to change qualitatively from those obtained using a cold beam outflow.

In the final section of Chapter 2 the time-dependent theory was applied to the case of the geomagnetic tail, where the assumptions regarding one-dimensionality are most nearly satisfied. Using neutral line motions expected on the basis of the neutral line model of substorms, and parameter values inferred from observations by the ISEE-3 spacecraft, a phenomenological substorm model was produced, in which the variations in the plasma sheet and energetic ion boundary layer thicknesses at a position 200 R_E downtail from the Earth were calculated. On the basis of this model it was expected that the quiet time plasma sheet would be quite thin, due to a slow reconnection rate, and the relatively close position of the neutral line. During substorms, when the reconnection rate is enhanced and the neutral line is further away from the point of observation a thicker plasma sheet is expected.

The predictions made using the theory set up in Chapter 2 were made using "typical" values of tail parameters, and therefore represent "typical" variations. In the following chapter a case study of an actual substorm event was made, in which the ISEE-3 spacecraft, located in the deep tail, observed variations of the plasma sheet and associated energetic ion boundary layers which did not, at first sight, match those expected on the basis of the theory. This event contained an extended period of quiet geomagnetic activity, followed by a single, isolated substorm. During the quiet period the plasma sheet flow speed was much lower than that expected on the basis of the "typical" parameters applied to the theory of the preceding chapter, and the plasma sheet thickness was much larger. However, these discrepancies can be accounted for if the theoretical values are recalculated using the highly untypical parameter values in the tail at the time of this event, such that the agreement between theory and observation is then quite good, indicating that the reconnection rate and location of the neutral line are not the only factors influencing the structure of the plasma sheet.

During the period of disturbed geomagnetic conditions the spacecraft clearly encountered a tailward propagating structure, and the associated post-plasmoid plasma sheet. The timings of the events during this period, compared to the

substorm onset, and the observed flow speeds and layer thicknesses are consistent with those expected from the time-dependent theory. The theoretical models developed in Chapter 2 of this thesis therefore form a useful basis on which the behaviour of the time dependent tail may be understood.

This event, and the seven others that were studied with it as part of the CDAW-8 workshop, also provided general support for the neutral line model of substorms, which was described in the introduction. However, several new aspects of tail dynamics were brought out, which are not included in the neutral line model. The first of these, occurring in three of the eight CDAW-8 periods during times of low or intermittent geomagnetic activity, is the observation of extended plasma sheet encounters during which the plasma sheet bulk speed is too low to be explained on the basis of stress balance on reconnected field lines, although all other plasma parameters are consistent with those observed in the reconnection associated plasma sheet shortly before or after these "slow plasma sheet" periods. Since it appears that these layers are located on the flanks of the tail we conclude that the plasma and field in these regions is undergoing tailward convection under the action of "viscous-like" stresses. Since the regions do not contain a magnetosheath-like component to the plasma population, the process must transfer momentum, but not mass, across the tail magnetopause, and these results would therefore support the suggestions of a Kelvin-Helmholtz instability operating at the magnetopause. As discussed in the introduction, the two processes causing magnetospheric convection, namely magnetic reconnection (Dungey, 1961) and "viscous" processes (Axford and Hines, 1961) may coexist on a continual basis, although the former process is dominant in all but the most quiet periods. The "slow plasma sheet" regimes observed in the CDAW-8 data sets are associated with the "viscous" process, whilst the observation of plasmoids, and most plasma sheet encounters are associated with reconnection. It is perhaps significant that extended intervals of "slow plasma sheet" occur during the periods of quiet, or intermittent geomagnetic activity.

One of the advantages of the neutral line model of substorms is its simple prediction of the formation and expulsion down the tail of the plasmoid structures. Although all of the plasmoids observed in the CDAW-8 data set can be related to a particular substorm onset, and therefore fit the neutral line model well, not all substorms result in the formation of plasmoids. Naturally the spacecraft will not always be in the correct position to observe the passage

of a plasmoid, although it appears that some disturbance enhancements may simply result in an increased reconnection rate at a pre-existing near-Earth neutral line, with no plasmoid structure. Such enhancements can, of course, be described using the time-dependent theory developed in Chapter 2, and the plasma sheet structures would be expected to expand under these circumstances. There is one clear example of plasma sheet expansion over the spacecraft (located in the deep tail) with no plasmoid observation in the CDAW-8 data set to support this scenario. This behaviour of the tail is not currently a feature of the neutral line model.

The application of the time-dependent model to the magnetic tail, discussed above, shows good agreement between the theory and observations if account is taken of the prevailing conditions in the tail, and thus lends support to the reconnection picture of substorms. However, this picture (as portrayed in the neutral line model) is still not universally accepted as the definitive model. Other models of substorm dynamics (e.g. Rostoker and Eastman, 1987), mostly driven by some kind of "viscous" interaction between the solar wind and magnetosphere, are still being proposed and discussed within the literature. There is consequently a continuing role for the models presented here to be used as a tool when comparing the virtues of the various models and their relationship to the observation. Also, the relative importance of these two types of model may be more easily determined if greater study of "typical" tail data were made. To date, most of the work published from the ISEE-3 data set has concerned "special" events, such as the observation of plasmoids, and other substorm associated phenomena. Studies of the more "typical" periods in the data set, may, for example reveal more "slow plasma sheet" regimes on the flanks of the reconnection associated plasma sheet, from which the exact nature of the "viscous" type interaction and its effects (cf. those of reconnection) may be determined.

The subject of one-dimensional stress balance of reconnected field lines was further considered in Chapter 4. The previous analyses of current sheet equilibrium discussed in the introduction to this thesis have assumed symmetrical inflow plasma conditions on the two sides of the current sheet. However, the ISEE-3 mission demonstrated that a large asymmetry in plasma density can exist between the two lobes of the geomagnetic tail, due to effects controlled by the GSE y-component of the interplanetary magnetic field, and theory also suggests that a simultaneous flow shear should also exist. In

Chapter 4 the current sheet equilibrium condition was generalized to include lobe plasma asymmetry under the simplifying assumption that all particles incident on the current sheet are transmitted through it. The result can be expressed in a form which emphasises the equivalence of stress balance by anisotropic plasma pressure and by net flow through the current sheet. The former case occurs for symmetrical lobe conditions, and balance is expressed in terms of the marginal firehose stability criterion. The latter case occurs if one lobe dominates, when the field-aligned plasma flow speed in the field line rest frame must equal the lobe Alfvén speed. The results of this theoretical work were illustrated by a simple example in which the inflow plasmas are approximated as cold ion beams of unequal density and speed, showing the structure of the resulting asymmetric plasma sheet and plasma outflow speeds. It was also shown that equilibrium solutions cease to exist if the inflow velocity shear becomes too large. However, this condition is most unlikely to be encountered in the tail.

In this thesis we have applied the theoretical work on current sheet stress balance to the geomagnetic tail, where the assumptions made to set up the model are most nearly valid. However, in principle, the models could be applied to other regions of the magnetosphere and solar system in which magnetic reconnection is a feature. For example, one possibility is the application of the models to the formation of flux transfer events (FTEs) on the dayside magnetopause. A qualitative model of FTEs, based on similar principles to that described in Chapter 1 has recently been published by Southwood et al. (1988). In this model the FTE is formed by a brief enhancement of the reconnection rate at the dayside magnetopause, and is analogous to the formation of plasmoids in the magnetotail configuration. However, a full treatment of FTE formation would require the combination of the two aspects of current sheet stress balance presented in this thesis, to account for the time dependent nature of the phenomenon and for the significant asymmetries which are likely to exist between the magnetosheath and the magnetopause. The work of Cowley and Southwood (1980), should also be incorporated, in order to include the effects of slow variations along the current sheet. Although such a model may prove useful as a basis to interpret observations, two fundamental aspects of flux transfer events are still neglected, namely the presence of finite B_y in the magnetosheath, such that the reconnecting magnetic fields may not be closely antiparallel, and the effects of

finite plasma β , such that the gas pressure perpendicular to the field direction could no longer be neglected in the analysis.

Chapter 5 of this thesis considered the energetic ion pitch angle distribution within the lobes of the magnetic tail. This has been a relatively neglected area of study in the past, the only related work being that of Pilipp and Morfill (1978), who considered thermal plasma transport in the lobes, and the consequences for the formation of the plasma sheet.

Observations of energetic ions ($E \geq 35$ keV) in the tail lobes made by the EPAS instrument on ISEE-3 showed that, under typical conditions, their pitch angle distribution is peaked closely perpendicular to the magnetic field direction (which points directly towards or away from the Earth in the tail), with a small tailward directed anisotropy in the flow. However, during solar particle events, when the solar wind flux of energetic ions is several orders of magnitude above its usual value, the distribution in the lobe is observed to be closely isotropic. The model presented in this thesis reproduces these characteristics by assuming a spatial gradient in the magnetosheath ion intensity under normal circumstances, with high fluxes close to the Earth, falling to the solar wind background flux with increasing distance down the tail. This gradient in ion intensity is assumed to be caused by the effects of particle energization at the bow shock, or by the escape of ring current energetic particles close to the Earth, or a combination of the two effects. The magnetopause separating the lobes from the magnetosheath can be considered open to particle entry to the lobes provided there is a component of the magnetic field threading the boundary. Under these circumstances the magnetosheath acts as a spatially varying source for the lobe energetic ions, and consideration of the particles' interaction with the magnetopause and their subsequent motion within the lobe allows the calculation of the pitch angle distribution at any point within the lobe. In this case the lobe is modelled as a simple two-dimensional box in which the field remains constant, except at the Earthward end, where a perfect mirror is applied. However, the inclusion of a more realistic increase in the field strength at the Earthward end of the box does not cause a qualitative change in the results. The theoretically derived results show a peak in pitch angle distribution at a few degrees above 90° , and generally higher values of f for particles moving tailwards along the field direction than for the particles moving Earthwards, in agreement with the observations. However, the exact nature of the distribution is dependent on position within the lobe, and the scale

length of the intensity variation within the magnetosheath. Hence the distributions observed during solar particle events can also be obtained from this model if it is assumed that the large energetic ion fluxes observed during such periods have no significant down-tail gradient, and are of sufficient intensity to mask those arising from the bow shock or from ring current escape.

The work presented in Chapter 5 has thus provided a description of the main observational features of the ion pitch angle distributions in the lobes, and puts forward a simple model that reproduces these basic features. However, there is scope for much more work in this area, especially on the observational side. The model, despite its simplicity, is capable of predicting the finer aspects of the pitch angle distribution, and how it varies with the position of observation within the lobes. However, some work remains to be done to determine the observed variations with, for example, distance down the tail, or from the magnetopause, in order that more direct comparisons between data and theory can be made. At the present time the model does not include any cross-tail dependence, although we expect to find such dependence in the data, controlled by the y-component of the interplanetary magnetic field. These effects could be readily included in the model by applying the principles described in Chapter 5 to a box in which the field is known in three dimensions.

In addition, some of the input parameters to the theory were at best qualitative. For example, the exact spatial variation of the ion intensity within the magnetosheath, which provides the source for the lobe distributions, is not at all well known. This is not easy to determine directly as simultaneous measurements from spacecraft located in the magnetosheath are required in order to separate temporal and spatial variations. Alternately, a statistical study could be useful, if all the magnetosheath periods from the tail data set are combined to give an "average" flux variation with distance downtail. However, it may be also possible to make an indirect measurement using the model proposed in Chapter 5. The pitch angle distribution is made up of particles which enter the lobe along the entire length of the magnetopause. Some measure of the sheath flux variation may therefore be obtained by working backwards in the model from an observed distribution and calculating the required intensity at each point along the magnetopause. Such a technique will have errors associated with the simplicity of the model, but may provide the "best guess" to the magnetosheath flux variation likely for some time.

REFERENCES

- Akasofu, S.-I., Energy coupling between the solar wind and the magnetosphere, **Space Sci. Rev.**, **28**, 121, 1981a.
- Alfvén, H., Some properties of magnetospheric neutral surfaces, **J. Geophys. Res.**, **73**, 4379, 1968.
- Anagnostopoulos, G.C., E.T. Sarris, and S.M. Krimigis, Magnetospheric origin of energetic ($E \geq 50$ keV) ions upstream of the bow shock: The October 31, 1977, event, **J. Geophys. Res.**, **91**, 3020, 1986.
- Arnoldy, R.L., Signature in the interplanetary medium for substorms, **J. Geophys. Res.**, **76**, 5189, 1971.
- Asbridge, J.R., S.J. Bame, J.T. Gosling, G. Paschmann, and N. Sckopke, Energetic plasma ions in the earth's magnetosheath, **Geophys. Res. Lett.**, **5**, 953, 1978.
- Axford, W. I., The interaction between the solar wind and the Earth's magnetosphere, **J. Geophys. Res.**, **67**, 3791, 1962.
- Axford, W. I. and C. O. Hines, A unifying theory of high latitude geophysical phenomena and geomagnetic storms, **Can. J. Phys.**, **39**, 1433, 1961.
- Axford, W.I., H.E. Petschek and G.L. Siscoe, Tail of the magnetosphere, **J. Geophys. Res.**, **70**, 1231, 1965.
- Baker, D.N., S.J. Bame, R.D. Belian, W.C. Feldman, J.T. Gosling, P.R. Higbie, E.W. Hones, Jr., D.J. McComas and R.D. Zwickl, Correlated dynamical changes in the near-earth and distant magnetotail regions: ISEE 3, **J. Geophys. Res.**, **89**, 3855, 1984a.
- Baker, D.N., S.J. Bame, J. Birn, W.C. Feldman, J.T. Gosling, E.W. Hones, Jr., R.D. Zwickl, J.A. Slavin, E.J. Smith, B.T. Tsurutani and D.G. Sibeck, Direct observations of passages of the distant neutral line (80-140 RE) following substorm onsets: ISEE 3 **Geophys. Res. Lett.**, **11**, 1042, 1984b.
- Baker D.N., J.D. Craven, R.C. Elphic, D.H. Fairfield, L.A. Frank, H.J. Singer, J.A. Slavin, I.G. Richardson, C.J. Owen and R.D. Zwickl, The CDAW-8 substorm event on 28 January 1983: A detailed global study, Submitted to **J. Geophys. Res.**, 1988.

Balogh, A., G. van Dijen, J. van Genechten, J. Henrion, R.J. Hynds, G. Korfmann, T. Iversen, J. van Rooijen, T. Sanderson, G. Stevens, and K-P. Wenzel, The low energy proton experiment on ISEE-C, **IEEE Trans. on Geoscience Electronics**, GE-16, No. 3, 176, 1978.

Bame, S.J., J.R. Asbridge, H.E. Felthausen, E.W. Hones and I.B. Strong, Characteristics of the plasma sheet in the Earth's magnetotail, **J. Geophys. Res.**, **72**, 113, 1967.

Bame S.J., J.R. Asbridge, H.E. Felthausen, J.P. Glore, H.C. Hawk, and J. Charez, ISEE-C solar wind plasma experiment, **IEEE Trans. on Geoscience Electronics**, GE-16, No. 3, 160, 1978.

Bame S.J., R.C. Anderson, J.R. Asbridge, D.N. Baker, J.T. Gosling, E.W. Hones Jr, D.J. McComas and R.D. Zwickl, Plasma regimes in the deep geomagnetic tail: ISEE-3, **Geophys. Res. Lett.**, **10**, 912, 1983.

Bavassano, B., F. Mariani and U. Villante, Far magnetospheric field observations by pioneer 8: the distant bow shock and the extended tail, **Space Res.**, **14**, 403, 1974.

Bieber J.W., E.C. Stone, E.W. Hones Jr, D.N. Baker and S.J. Bame, Plasma behaviour during energetic electron streaming events: Further evidence for substorm associated magnetic reconnection, **Geophys. Res. Lett.**, **9**, 664, 1982.

Biermann, L., Kometenschweife und solare Korpuskularstrahlung, **Zs. f. Ap.**, **29**, 274, 1951.

Biermann, L., Solar corpuscular radiation and the interplanetary gas, **Observatory**, **77**, 109, 1957.

Bird, M.K., and D.B. Beard, The self-consistent geomagnetic tail under static conditions, **Planet. Space Sci.**, **20**, 2057, 1972.

Birn, J., R.R. Sommer, and K. Schindler, Open and closed magnetospheric tail configurations and their stability, **Astrophys. Space Sci.**, **35**, 389, 1975.

Birn, J., R.R. Sommer, and K. Schindler, Self-consistent theory of the quiet geomagnetic tail in three dimensions, **J. Geophys. Res.**, **82**, 147, 1977.

Chao, J.K., J.R.Kan, A.T.Y. Lui and S-I Akasofu, A model for thinning of the plasma sheet, **Planet. Space Sci.**, **25**, 703, 1977.

Chapman, S. and V. C. A. Ferraro, A new theory on magnetic storms, **Terr. Mag. Atmos. Elec.**, **36**, 77-97, 171-186, 1931; **37**, 147-156, 421-429, 1932; **38**, 79-96, 1933.

Coleman, P.J., Jr., L. Davies, and C. P. Sonett, Steady component of the interplanetary magnetic field: Pioneer V, **Phys. Rev. Lett.**, **5**, 43-46, 1960.

Coroniti, F.V., Explosive tail reconnection: the growth and expansion phases of magnetic substorms, **J. Geophys. Res.**, **90**, 7477, 1985.

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

Coriniti, F.V., L.A. Frank, D.J. Williams, R.P. Lepping, F.L. Scarf, S.M. Krimigis and G. Gloeckler, Variability of plasma sheet dynamics, **J. Geophys. Res.**, **85**, 2957, 1980.

Cowley, S.W.H., A self-consistent model of a simple magnetic neutral sheet system surrounded by a cold, collisionless plasma, **Cosmic Electrodyn.**, **3**, 338, 1973.

Cowley, S.W.H., Plasma populations in a simple open model magnetosphere, **Space Sci. Rev.**, **25**, 217, 1980.

Cowley, S.W.H., Magnetospheric asymmetries associated with the y-component of the IMF, **Planet. Space Sci.**, **29**, 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.

Cowley, S.W.H., Solar wind control of magnetospheric convection, in **Achievements of the International Magnetospheric Study IMS**, ESA SP-217, ESTEC, Noordwijk, The Netherlands, p.483, 1984a.

Cowley, S.W.H., The distant geomagnetic tail in theory and observation, in **Magnetic Reconnection in Space and Laboratory Plasmas**, **Geophys.**

Monogr. Ser., vol. 30, ed. E.W. Hones, Jr., pp.228-239, AGU, Washington, D.C., 1984b.

Cowley, S.W.H., and R. Pellat, A note on adiabatic solutions of the one dimensional current sheet problem. **Planet. Space Sci.**, **27**, 265, 1979.

Cowley, S.W.H. and D.J. Southwood, Some properties of a steady state geomagnetic tail, **Geophys. Res. Lett.**, **7**, 833, 1980.

Cowley, S.W.H., R.J. Hynds, I.G. Richardson, P.W. Daly, T.R. Sanderson, K.-P. Wenzel, J.A. Slavin, and B.T. Tsurutani, Energetic ion regimes in the deep geomagnetic tail: ISEE 3, **Geophys. Res. Lett.**, **11**, 275, 1984.

Crooker, N.U., T.E. Eastman, L.A. Frank, E.J. Smith, and C.T. Russell, Energetic magnetosheath ions and the interplanetary magnetic field orientation, **J. Geophys. Res.**, **86**, 4455, 1981.

Daly, P.W., T.R. Sanderson, and K.-P. Wenzel, Survey of energetic ($E \geq 35$ keV) ion anisotropies in the deep geomagnetic tail, **J. Geophys. Res.**, **89**, 10733, 1984.

Decoster, R.J. and L.A. Frank, Observations pertaining to the dynamics of the plasma sheet, **J. Geophys. Res.**, **84**, 5099, 1979.

DeHoffman, F., and E. Teller, Magneto-hydrodynamic shocks, **Phys. Rev.**, **80**, 692, 1950.

Dessler, A.J., Length of magnetospheric tail, **J. Geophys. Res.**, **69**, 3913, 1964.

Dungey, J.W., Conditions for the occurrence of electric discharge in astrophysical systems, **Phil Mag.**, **44**, 725, 1953.

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

Dungey, J.W., The length of the magnetospheric tail, **J. Geophys. Res.**, **70**, 1753, 1965.

Eastman, T.E. and E.W. Hones, Jr., Characteristics of the magnetospheric boundary layer and magnetopause layer as observed by IMP 6, **J. Geophys. Res.**, **84**, 2019, 1979.

Eastman, T.E., E.W. Hones, Jr., S.J. Bame and J.R. Asbridge, The magnetospheric boundary layer: Site of plasma, momentum and energy transfer from the magnetosheath into the magnetosphere, **Geophys. Res. Lett.**, **3**, 685, 1976.

Eastwood, J.W., Consistency of fields and particle motion in the "Speiser" model of the current sheet, **Planet. Space Sci.**, **20**, 1555, 1972.

Eastwood, J.W., The warm current sheet model and its implications on the behaviour of the geomagnetic tail, **Planet. Space Sci.**, **22**, 1641, 1974.

Fairfield, D.H. and L.J. Cahill, Jr., Transition region magnetic field and polar magnetic disturbances, **J. Geophys. Res.**, **71**, 155, 1966.

Fairfield, D.H., R.P. Lepping, E.W. Hones, Jr., S.J. Bame and J.R. Asbridge, Simultaneous measurements of magnetotail dynamics by IMP spacecraft, **J. Geophys. Res.**, **86**, 1396, 1981.

Ferraro, V.C.A., On the theory of the first phase of a geomagnetic storm: A new illustrative calculation based on an idealised (plane not cylindrical) model field distribution, **J. Geophys. Res.**, **57**, 15, 1952.

Ferraro, V.C.A., An approximate method of estimating the size and shape of the stationary hollow carved out in a neutral ionized stream of corpuscles impinging on the geomagnetic field, **J. Geophys. Res.**, **65**, 3951, 1960.

Forbes, T.G., E.W. Hones, Jr., S.J. Bame, J.R. Asbridge, G. Paschmann, N. Sckopke, and C.T. Russell, Evidence for tailward retreat of a magnetic neutral line in the magnetotail during substorm recovery, **Geophys. Res. Lett.**, **8**, 261, 1981.

Francfort, Ph., and R. Pellat, magnetic merging in collisionless plasmas, **Geophys. Res. Lett.**, **3**, 433, 1976.

Frandsen, A.M.A., B.V. Connor, J. van Amersfoort and E.J. Smith, The ISEE-C vector helium magnetometer, **IEEE Trans. on Geoscience Electronics**, GE-16, No. 3, 195, 1978.

Frank, L.A., A survey of electrons E40 kev beyond 5 Earth radii with Explorer 14, **J. Geophys. Res.**, **70**, 1593, 1965.

Gold, T, Magnetic storms, **Space Sci. Rev.**, **1**, 100, 1962.

Gosling J.T., D.N. Baker, S.J. Bame, E.W. Hones Jr., D.J. McComas, R.D. Zwickl, J.A. Slavin, E.J. Smith, B.T. Tsurutani, Plasma entry into the distant tail lobes: ISEE-3, **Geophys. Res. Lett.**, **11**, 1078, 1984

Gosling, J.T., D.N. Baker, S.J. Bame, W.C. Feldman, R.D. Zwickl, and E.J. Smith, North-South and dawn-dusk plasma asymmetries in the distant tail lobes: ISEE-3, **J. Geophys. Res.**, **90**, 6354, 1985.

Gringauz, V., G. Kurt, V. I. Moroz, and I.S. Shklovskii, Ionized gas and fast electrons in the vicinity of the Earth and in interplanetary space, **Planet. Space Sci.**, **9**, 21, 1962.

Heikkila, W. J., Impulsive plasma transport through the magnetopause, **Geophys. Res. Lett.**, **9**, 159, 1982.

Heikkila, W.J., Neutral sheet crossings in the distant magnetotail, in **Magnetotail Physics**, ed A.T.Y. Lui, John Hopkins University press, p64, 1987.

Heppner, J.P., N.F. Ness, C.S. Searce and T.L. Skillman, Explorer 10 magnetic field measurements, **J. Geophys. Res.**, **68**, 1, 1963.

Hill, T.W., Magnetic merging in a collisionless plasma, **J. Geophys. Res.**, **80**, 4689, 1975.

Hines, C. O., The magnetopause: a new frontier in space, **Science**, **141**, 130, 1960.

Hones, E.W., Jr., The magnetotail: its generation and dissipation, in "Physics of Solar Planetary Environments", Ed. D.J. Williams, AGU Washington, p558, 1976.

Hones, E.W., Jr., Transient phenomena in the magnetotail and their relation to substorms, **Space Sci. Rev.**, **23**, 393, 1979.

Hones, E.W., Jr., Plasma flow in the magnetotail and its implications for substorm theories, in **"Dynamics of the Magnetosphere"**, Ed. S-I Akasofu, D.Reidel, p 545, 1980.

Hones, E.W., Jr., Plasma sheet behaviour during substorms, in **Magnetic Reconnection in Space and Laboratory Plasmas**, **Geophys. Monogr. Ser.**, vol. 30, ed. E.W. Hones, Jr., pp.178-184, AGU, Washington, D.C., 1984.

Hones, E.W., Jr., Plasma flow in the near and distant geomagnetic tail, **Adv. Space Res.**, vol.5, no. 4, pp.375-388, 1985.

Hones, E.W., Jr., J. Birn, D.N. Baker, S.J. Bame, W.C. Feldman, D.J. McComas, R.D. Zwickl, J.A. Slavin, E.J. Smith, and B.T. Tsurutani, Detailed examination of a plasmoid in the distant magnetotail with ISEE 3, **Geophys. Res. Lett.**, **11**, 1046, 1984.

Hones, E.W., Jr, D.N. Baker, S.J. Bame, W.C. Feldman, J.T. Gosling, D.J. McComas, R.D. Zwickl, J.A. Slavin, E.J. Smith, and B.T. Tsurutani, Structure of the magnetotail and its response to geomagnetic activity, **Geophys. Res. Lett.**, **11**, 5, 1984b.

Jorgensen, T.S., E. Friis-Christensen and J. Wilhjelm, Interplanetary magnetic-field direction and high-latitude ionospheric currents, **J. Geophys. Res.**, **77**, 1976, 1972.

Lee, M.A., Coupled hydromagnetic wave excitation and ion acceleration upstream of the Earths bow shock, **J. Geophys. Res.**, **87**, 5063, 1982.

Lemaire, J., Impulsive penetration of filamentary plasma elements into the magnetospheres of the Earth and Jupiter, **Planet. Space Sci.**, **25**, 887, 1977.

Lui, A.T.Y. Lui, Roadmap to the magnetotail domains, in **Magnetotail Physics**, ed A.T.Y. Lui, John Hopkins University press, 1987.

Lui, A.T., E.W. Hones, Jr., D. Venkatesan, S.-I. Akasofu and S.J. Bame, Complete plasma dropouts at Vela satellites during thinning of the plasma sheet, **J. Geophys. Res.**, **80**, 4649, 1975.

- Lyons, L.R. and T.W. Speiser, Evidence for current sheet acceleration in the geomagnetic tail, **J. Geophys. Res.**, **87**, 2276, 1982.
- McPherron, R.L., Growth phase of magnetospheric substorms, **J. Geophys. Res.**, **75**, 5592, 1970.
- Ness, N.F., The Earth's magnetic tail, **J. Geophys. Res.**, **70**, 2989, 1965.
- Nishida, A., and N. Nagayama, Synoptic survey for the neutral line in the magnetotail during the substorm expansion phase, **J. Geophys. Res.**, **78**, 3782, 1973.
- Parker, E. N., Dynamics of the interplanetary gas and magnetic fields, **Astrophys. J.**, **128**, 664, 1958a.
- Parker, E. N., Interaction of the solar wind with the geomagnetic field, **Phys. Fluid**, **1**, 171, 1958b.
- Parks, G.K., C.S. Lin, K.A. Anderson, R.P. Lin and H. Reme, ISEE 1 and 2 particle observations of outer plasma sheet boundary, **J. Geophys. Res.**, **84**, 6471, 1979,
- Paulikas, G.A., Tracing of high latitude magnetic field lines by solar particles, **Rev. Geophys. Space Phys.**, **12**, 117, 1974.
- Petschek, H.E., Magnetic field annihilation, AAS-NASA Symposium on the Physics of Solar Flares, **NASA Spec. Publ. SP-50**, 425, 1964
- Pilipp, W.G. and G. Morfill, The formation of the plasma sheet resulting from plasma mantle dynamics, **J. Geophys. Res.**, **83**, 5670, 1978.
- Rich, F.J., V.M. Vasyliunas, and R.A. Wolf, On the balance of stresses in the plasma sheet, **J. Geophys. Res.**, **77**, 4670, 1972.
- Richardson, I.G., and S.W.H. Cowley, Plasmoid associated energetic ion bursts in the deep geomagnetic tail: Properties of the boundary layer, **J. Geophys. Res.**, **90**, 12133, 1985.

Richardson, I.G., and S.W.H. Cowley, Plasmoid associated energetic ion bursts in the distant magnetotail, in **AGU Monogr. on Magnetotail Physics**, ed. A.T.Y. Lui, 1986.

Richardson, I.G., S.W.H. Cowley, E.W. Hones Jr., S.J. Bame, Plasmoid associated energetic ion bursts in the deep geomagnetic tail: Properties of plasmoids and the post plasmoid plasma sheet, **J. Geophys. Res.**, **92**, 9997, 1987.

Richardson, I.G., C.J. Owen, S.W.H. Cowley, A.B. Galvin, T.R. Sanderson, M. Scholer, J.A. Slavin, R.D. Zwickl, ISEE-3 Observations during the CDAW-8 intervals: Case studies of the distant geomagnetic tail covering a wide range of geomagnetic activity, submitted to **J. Geophys. Res.**, 1988.

Rostoker, G. and Eastman, T., A boundary layer model for magnetospheric substorms, **J. Geophys. Res.**, **92**, 12187, 1987.

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

Sanderson, T.R., and R.J. Hynds, Multiple telescope measurements of particle anisotropies in space, **Planet. Space Sci.**, **25**, 799, 1977.

Sarris, E.T. G.C. Anagnostopoulos and S.M. Krimigis, Simultaneous measurements of energetic ion (50 keV) and electron (220 keV) activity upstream of the Earth's bow shock and inside the plasma sheet: Magnetospheric source for the November 3 and December 3, 1977 upstream events, **J. Geophys. Res.**, **92**, 12083, 1987.

Schindler K., A self consistent theory of the tail of the magnetosphere, in **Earth's Magnetospheric Processes** (Ed. by B. McCormac), p200, D. Reidel, Dordrecht (1972).

Schindler, K., A theory of the substorm mechanism, **J. Geophys. Res.**, **79**, 2803, 1974.

Schindler, K., On the role of irregularities of plasma entry into the magnetosphere, **J. Geophys. Res.**, **84**, 7257, 1979.

Scholer, M., F.M. Ipavich, G. Gloeckler, D. Hovestadt and B. Klecker, Leakage of magnetospheric ions into the magnetosheath along reconnected field lines at the dayside magnetopause, **J. Geophys. Res.**, **86**, 1299, 1981.

Scholer, M., D. Hovestadt, B. Klecker, G. Gloeckler, F.M. Ipavich, Average flow between 70 R_E and 220 R_E in the geomagnetic tail, **Geophys. Res. Lett.**, **11**, 343, 1984.

Scholer, M., D.N. Baker, G. Gloeckler, B. Klecker, F.M. Ipavich, T. Terasawa, B.T. Tsurutani and A.B. Galvin, Energetic particle beams in the plasma sheet boundary layer following substorm expansion: Simultaneous near-Earth and distant tail observations, **J. Geophys. Res.**, **91**, 4277, 1986.

Sibeck, D.G., G.L. Siscoe, J.A. Slavin, E.J. Smith, B.T. Tsurutani, and R.P. Lepping, The distant magnetotails response to a strong interplanetary magnetic field B_y: Twisting, flattening and field line bending, **J. Geophys. Res.**, **90**, 4011, 1985.

Sibeck, D.G., G.L. Siscoe, J.A. Slavin, R.P. Lepping, Major flattening of the geomagnetic tail, **J. Geophys. Res.**, **91**, 4223, 1986.

Sibeck, D.G., J.A. Slavin, and E.J. Smith, ISEE-3 magnetopause crossings: Evidence for the Kelvin-Helmholtz instability, in **Magnetotail Physics**, ed A.T.Y. Lui, John Hopkins University press, 1987a.

Sibeck, D.G., R.W. McEntire, A.T.Y. Lui, S.M. Krimigis, L.J. Zanetti, and T.A. Potemra, The magnetosphere as a source of energetic magnetosheath ions, **Geophys. Res. Lett.**, **14**, 1011, 1987b.

Slavin, J.A., E.J. Smith, B.T. Tsurutani, D.G. Sibeck, H.J. Singer, D.N. Baker, J.T. Gosling, E.W. Hones, Jr., and F.L. Scarf, Substorm associated travelling compression regions in the distant tail: ISEE 3 geotail observations, **Geophys. Res. Lett.**, **11**, 657, 1984.

Slavin, J.A., E.J. Smith, D.G. Sibeck, D.N. Baker, R.D. Zwickl, and S.-I. Akasofu, An ISEE 3 study of average and substorm conditions in the distant magnetotail, **J. Geophys. Res.**, **90**, 10875, 1985.

Smith, E.J., A comparison of Explorer VI and Explorer X magnetometer data, **J. Geophys. Res.**, **67**, 2045, 1962.

Smith, E.J., C.P. Sonett and J.W. Dungey, Satellite observations of the geomagnetic field during magnetic storms, **J. Geophys. Res.**, **69**, 2669, 1964.

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

Sonett, C. P., D. L. Judge, A. R. Sims, J. M. Kelso, A radial rocket survey of the distant geomagnetic tail, **J. Geophys. Res.**, **65**, 55, 1960.

Sonnerup, B.U.O., Magnetic field reconnection, in **Solar System Plasma Physics**, Vol. 3, ed. L.T Lanzerotti, C.F. Kennel, and E.N. Parker, North Holland, Amsterdam, p.45, 1979.

Sonnerup, B.U.O., G. Paschmann, I. Papamastorakis, N. Sckopke, G. Haerendel, S.J. Bame, J.R. Asbridge, J.T. Gosling and C.T. Russell, Evidence for magnetic reconnection at the Earth's magnetopause, **J. Geophys. Res.**, **86**, 10049, 1981.

Southwood, D. J., Magnetopause Kelvin-Helmholtz instability, in **Magnetospheric Boundary Layers**, Spec. Publ. ESA SP-148, ed. B. Battick, ESA, Noordwijk, Netherlands, p.357, 1979.

Southwood D.J., C.J. Farrugia, and M.A. Saunders, What are flux transfer events?, **Planet. Space Sci.**, **36**, 503, 1988.

Speiser, T.W., Particle trajectories in model current sheets, 1. Analytical solutions, **J. Geophys. Res.**, **70**, 4219, 1965.

Speiser, T.W., Particle trajectories in model current sheets, 2. Applications to auroras using a geomagnetic tail model, **J. Geophys. Res.**, **72**, 3919, 1967.

Speiser, T.W., On the uncoupling of parallel and perpendicular motion in a neutral sheet, **J. Geophys. Res.**, **73**, 1113, 1968.

Speiser, T.W. and L.R. Lyons, Comparison of an analytical approximation for particle motion in a current sheet with precise numerical calculations, **J. Geophys. Res.**, **89**, 147, 1984.

Spreiter, J. R., A. L. Summers, A. Y. Alksne, Hydromatic flow around the magnetosphere, **Planet. Space Sci.**, **14**, 223, 1966.

Tsurutani, B.T. and T.T. von Rosenvinge, ISEE 3 distant geotail results, **Geophys. Res. Lett.**, **11**, 1027, 1984.

Tsurutani, B.T., B.E. Goldstein, M.E. Burton, and D.E. Jones, A review of the ISEE-3 geotail magnetic field results, **Planet. Space Sci.**, **34**, 931, 1986.

Tsurutani, B.T., M.E. Burton, E.J. Smith, D.E. Jones, R.P. Lepping and A.J. Lazarus, Distant (200-238 RE) magnetotail lobe characteristics during quiet solar wind conditions, **Planet. Space Sci.**, **35**, 285, 1987.

Van Allen, J. A. and L. A. Frank, Radiation around the Earth to a radial distance of 107400 km, **Nature**, **183**, 430, 1959a.

Van Allen, J. A. and L. A. Frank, Radiation measurements to 658,300 km with Pioneer IV, **Nature**, **184**, 219, 1959b.

van Rooijen, J.J., G.J. van Dijen, H. Th. Lafleur and P. Lowes, A low energy proton spectrometer for directional distribution measurements in space, **Space Sci. Instrum.**, **4**, 373, 1979.

Walker, R.C., U. Villante and A.J. Lazarus, Pioneer 7 observations of plasma flow and field reversal regions in the distant geomagnetic tail, **J. Geophys. Res.**, **80**, 1238, 1975.

Wilcox, J.M., K.H. Schatten and N.F. Ness, Influence of interplanetary magnetic field and plasma on geomagnetic activity during quiet-Sun conditions, **J. Geophys. Res.**, **72**, 19, 1967.

Williams D.J., Energetic ion beams at the edge of the plasma sheet, ISEE 1 observations plus a simple explanatory model, **J. Geophys. Res.**, **86**, 5507, 1981.

Williams D.J., D.G. Mitchell, L.A. Frank, T.E. Eastman, Three- dimensional magnetosheath plasma ion distributions 200eV - 2 MeV, in press, 1988.

Zwickl, R.D., D.N. Baker, S.J. Bame, W.C. Feldman, J.T. Gosling, E.W. Hones, Jr., D.J. McComas, B.T. Tsurutani and J.A. Slavin, Evolution of the Earth's distant magnetotail: ISEE 3 electron plasma results, **J. Geophys. Res.**, **89**, 11007, 1984.