Dynamic Pressure Pulses in Earth’s Dayside Magnetosheath

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Abstract

Solar wind mass, energy and momentum can be transferred to Earth’s magnetosphere at the magnetopause with the shocked magnetosheath acting as an interface between the two regions. In particular the magnetosheath pressure is important in terms of the position and motion of the magnetopause, which in turn can have effects throughout the dayside magnetosphere. A variety of transient phenomena often occur in the magnetosheath and in this thesis one example is studied, namely pulses in the magnetosheath dynamic pressure, using multipoint spacecraft observations to investigate their origins and magnetospheric impacts and illuminate dayside magnetospheric dynamics.

Simultaneous observations in the solar wind, foreshock and magnetosheath reveal an interval of dynamic pressure pulses that did not exist upstream of the bow shock in the pristine solar wind or foreshock and appear consistent with previous simulations of solar wind discontinuities interacting with the bow shock, which predict large amplitude pulses when the local geometry of the shock changes. A statistical study of these structures, however, reveals their predominant origin near the quasi-parallel shock, typically under steady interplanetary magnetic fields, suggestive that the foreshock is important in their generation. The enhanced pressure on the magnetopause due to these pulses can perturb the boundary, exciting ultra-low frequency waves in the magnetosphere and travelling convection vortices in the ionosphere, similar to the response to pressure variations of solar wind origin. However, in this case the response is smoother and on longer timescales than the sharp, impulsive pressure variations and often a collective effect of numerous pulses.

Conditions at the magnetopause are often inferred from suitably time lagged measurements of the pristine solar wind taken far upstream of Earth at the L1 Lagrangian point. However, such methods cannot predict the precise locations and times of dynamic pressure pulses in the magnetosheath, which directly drive magnetospheric dynamics.
Declarations

I hereby declare that the work presented in this thesis is my own and all other work has been appropriately referenced. The studies carried out during the course of this degree has lead to the publication of the following peer-reviewed scientific papers (results from the first three of which are presented in this thesis):


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First and foremost, I would like to thank my supervisor Tim Horbury. Had it not been for his engaging tutorials in the second year of my undergraduate degree, I may not have ended up in this field of research. He has been a great source of guidance and encouragement and has honoured my ideas in both this research and in public outreach. I am also grateful to my collaborators Jonathan Eastwood, Tim Yeoman, and James Weygand who have provided valuable input into the work in this thesis. Further thanks must go to colleagues in the Space and Atmospheric Physics Group at Imperial College London whom I have had fruitful discussions with over the course of the degree including Robert Wickes, Jeremy Mitchell, Lorenzo Matteini and Heli Hietala.

I would like to make particular mention of my friend Peter Shardlow, without whom this thesis would not exist. It was in a pub after having visited the Royal Institution of Great Britain that he planted the seed in my head of pursuing a PhD and for that I am very grateful. Over the course of this degree I have been fortunate enough to work on a number of exciting public outreach projects, so I would like to thank all the people at the BBC, Sky News, Channel 5, CNN, Al Jazeera, James May’s Head Squeeze, Royal Institution of Great Britain, Royal Society, Cheltenham Science Festival and the British Science Association that I have had the pleasure of working with and hope to continue to do so.

Finally, I would like to thank my parents for their continued support in all aspects of my life.
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<tbody>
<tr>
<td>$\alpha$</td>
<td>IMF clock angle</td>
</tr>
<tr>
<td>$\alpha_P$</td>
<td>Pressure anisotropy factor</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Plasma beta - ratio of thermal and magnetic pressures</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Adiabatic index - usually 5/3</td>
</tr>
<tr>
<td>$\epsilon_0$</td>
<td>Permittivity of free space - $8.854 \times 10^{-12}$ m$^{-3}$ kg$^{-1}$ s$^4$ A$^2$</td>
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<tr>
<td>$\Lambda$</td>
<td>Geomagnetic latitude</td>
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<tr>
<td>$\lambda_D$</td>
<td>Debye length</td>
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<td>$\Phi$</td>
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<td>$\theta_{Bk}$</td>
<td>Wavevector - magnetic field angle</td>
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<td>Cone angle (between the IMF and Sun-Earth line)</td>
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<td>$\theta_{Bn}$</td>
<td>Shock normal - interplanetary magnetic field angle</td>
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<td>$\theta_{vn}$</td>
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<td>$\omega$</td>
<td>Angular frequency</td>
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<td>Electron plasma frequency</td>
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<tr>
<td>$\omega_{pi}$</td>
<td>Ion plasma frequency</td>
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<tr>
<td>$\Omega_g$</td>
<td>Gyrofrequency (or cyclotron frequency)</td>
</tr>
<tr>
<td>3DP</td>
<td>Three-dimensional plasma and energetic particle investigation aboard WIND</td>
</tr>
<tr>
<td><strong>A</strong></td>
<td>Azimuthal component pointing east</td>
</tr>
<tr>
<td><strong>ACE</strong></td>
<td>Advanced Composition Explorer</td>
</tr>
<tr>
<td><strong>aGSE</strong></td>
<td>Aberrated GSE coordinates</td>
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<tr>
<td><strong>AU</strong></td>
<td>Astronomical Unit - mean Earth-Sun distance - 149,597,871 km</td>
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<tr>
<td><strong>B</strong></td>
<td>Magnetic field</td>
</tr>
<tr>
<td><strong>B_0</strong></td>
<td>Background magnetic field</td>
</tr>
<tr>
<td><strong>BATS-R-US</strong></td>
<td>Block-Adaptive-Tree-Solarwind-Roe-Upwind-Scheme MHD model</td>
</tr>
<tr>
<td><strong>bs</strong></td>
<td>Bow Shock</td>
</tr>
<tr>
<td><strong>c</strong></td>
<td>Speed of light - ( 2.998 \times 10^8 ) m s(^{-1})</td>
</tr>
<tr>
<td><strong>CANMOS</strong></td>
<td>Canadian Magnetic Observatory System</td>
</tr>
<tr>
<td><strong>CARISMA</strong></td>
<td>Canadian Array for Realtime Investigations of Magnetic Activity</td>
</tr>
<tr>
<td><strong>CCDF</strong></td>
<td>Complementary cumulative distribution function</td>
</tr>
<tr>
<td><strong>CD</strong></td>
<td>Contact discontinuity</td>
</tr>
<tr>
<td><strong>CDPS</strong></td>
<td>Cold and dense plasma sheet</td>
</tr>
<tr>
<td><strong>c_{ms}</strong></td>
<td>Magneto sonic speed</td>
</tr>
<tr>
<td><strong>c_s</strong></td>
<td>Sound speed</td>
</tr>
<tr>
<td><strong>D</strong></td>
<td>Geomagnetic East GMAG component</td>
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<tr>
<td><strong>DD</strong></td>
<td>Directional discontinuity</td>
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<tr>
<td><strong>d_i</strong></td>
<td>Ion inertial length</td>
</tr>
<tr>
<td><strong>DTU</strong></td>
<td>Technical University of Denmark</td>
</tr>
<tr>
<td><strong>E</strong></td>
<td>Electric field</td>
</tr>
<tr>
<td><strong>e</strong></td>
<td>Electronic charge - (-1.602 \times 10^{-19}) C</td>
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<tr>
<td><strong>ED</strong></td>
<td>“Either” a Rotational or Tangential Discontinuity</td>
</tr>
<tr>
<td><strong>EFI</strong></td>
<td>Electric field instrument</td>
</tr>
<tr>
<td><strong>EIC</strong></td>
<td>Equivalent Ionospheric Current</td>
</tr>
<tr>
<td><strong>ESA</strong></td>
<td>Electrostatic analyser</td>
</tr>
<tr>
<td><strong>F</strong></td>
<td>Field aligned component</td>
</tr>
<tr>
<td><strong>F</strong></td>
<td>Fractional magnetosheath distance</td>
</tr>
<tr>
<td><strong>FAC</strong></td>
<td>Field-Aligned Current</td>
</tr>
<tr>
<td><strong>FE</strong></td>
<td>Fast expansion wave</td>
</tr>
<tr>
<td><strong>f_{FLR}</strong></td>
<td>Fundamental FLR frequency</td>
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<tr>
<td><strong>FGM</strong></td>
<td>Fluxgate magnetometer</td>
</tr>
<tr>
<td><strong>FLR</strong></td>
<td>Field Line Resonance</td>
</tr>
<tr>
<td><strong>f_s</strong></td>
<td>6-dimensional phase space density of species ( s )</td>
</tr>
</tbody>
</table>
Nomenclature

FTE  Flux Transfer Event
$f_{uw}$  Upstream wave frequency
FWHM  Full width at half maximum
GIMA  Geophysical Institute Magnetometer Array
GOES  Geostationary Operational Environmental Satellites
GSE  Geocentric Solar Ecliptic coordinate system
GSM  Geocentric Solar Magnetic coordinate system
$H(f)$  Magnetopause pressure transfer function
HFA  Hot Flow Anomaly
HF  High frequency
H  Geomagnetic North GMAG component
IMF  Interplanetary Magnetic Field
j  Current density
k  Wave vector
k  Wavenumber
$k_B$  Boltzmann constant - $1.381 \times 10^{-23}$ m² kg s² K⁻¹
L  L-shell parameter
l  Typical length scale
LLBL  Low Latitude Boundary Layer
$M_A$  Alfvénic Mach number
MACCS  Magnetometer Array for Cusp and Cleft Studies
MCP  Microchannel plate
$m_e$  Mass of the electron - $9.109 \times 10^{-31}$ kg
MFA  Mean field aligned coordinate system
MFI  Magnetic Field Instrument aboard WIND
MHD  Magnetohydrodynamics
MIE  Magnetic Impulse Event
MLT  Magnetic Local Time
$M_{ms}$  Magnetosonic Mach Number
$mp$  Magnetopause
$msh$  Magnetosheath
MVA  Minimum Variance Analysis
n  Normal to discontinuity/shock
n  Number density (of electrons $n_e$; of ions $n_i$)
<table>
<thead>
<tr>
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<th>Description</th>
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<tr>
<td>ND</td>
<td>“Neither” a Rotational or Tangential Discontinuity</td>
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<tr>
<td>OMNI</td>
<td>Database of solar wind conditions lagged to the bow shock nose</td>
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<tr>
<td>( P )</td>
<td>Power spectral density</td>
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<tr>
<td>( P_{pow} )</td>
<td>Background power law fit</td>
</tr>
<tr>
<td>Pc</td>
<td>Continuous Pulsation</td>
</tr>
<tr>
<td>Pi</td>
<td>Irregular Pulsation</td>
</tr>
<tr>
<td>( P_B )</td>
<td>Magnetic pressure</td>
</tr>
<tr>
<td>PDF</td>
<td>Probability density function</td>
</tr>
<tr>
<td>( P_{dyn} )</td>
<td>Dynamic pressure</td>
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<td>( P_r )</td>
<td>Radially inwards pressure</td>
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<td>( \mathbf{P}_s )</td>
<td>Pressure tensor of species ( s )</td>
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<tr>
<td>( P_{th} )</td>
<td>Thermal pressure</td>
</tr>
<tr>
<td>( P_{th+B} )</td>
<td>Sum of thermal and magnetic pressures</td>
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<tr>
<td>( P_{tot} )</td>
<td>Total pressure (thermal + magnetic + dynamic)</td>
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<tr>
<td>( q )</td>
<td>Electric charge</td>
</tr>
<tr>
<td>( \mathbf{R} )</td>
<td>Radial component pointing towards Earth</td>
</tr>
<tr>
<td>( r )</td>
<td>Distance</td>
</tr>
<tr>
<td>RD</td>
<td>Rotational discontinuity</td>
</tr>
<tr>
<td>( r_g )</td>
<td>Gyroradius (or Larmor radius)</td>
</tr>
<tr>
<td>( R_m )</td>
<td>Magnetic Reynolds number</td>
</tr>
<tr>
<td>( \mathbf{R}_s )</td>
<td>Rate of momentum increase due to collisions</td>
</tr>
<tr>
<td>SEA</td>
<td>Superposed Epoch Analysis</td>
</tr>
<tr>
<td>SEMS</td>
<td>Space Environment Monitoring Subsystems aboard GOES spacecraft</td>
</tr>
<tr>
<td>SLAMS</td>
<td>Short Large Amplitude Magnetic Structures</td>
</tr>
<tr>
<td>( sph )</td>
<td>Magnetosphere</td>
</tr>
<tr>
<td>SS</td>
<td>Slow shock</td>
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<tr>
<td>STEP</td>
<td>Solar-Terrestrial Energy Program</td>
</tr>
<tr>
<td>SuperDARN</td>
<td>Super Dual Auroral Radar Network</td>
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<tr>
<td>( sw )</td>
<td>Solar Wind</td>
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<tr>
<td>SWEPAM</td>
<td>Solar Wind Electron, Proton, and Alpha Monitor aboard ACE</td>
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<td>SWE</td>
<td>Solar Wind Experiment aboard WIND</td>
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<td>( T )</td>
<td>Temperature (of electrons ( T_e ); of ions ( T_i ); of protons ( T_p ))</td>
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<td>T96</td>
<td>Tsyganenko Geomagnetic Field Model (1996)</td>
</tr>
<tr>
<td>TCV</td>
<td>Travelling Convection Vortex</td>
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### Nomenclature

<table>
<thead>
<tr>
<th>TD</th>
<th>Tangential discontinuity</th>
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<tbody>
<tr>
<td>TFE</td>
<td>Transient Flux Event</td>
</tr>
<tr>
<td>THEMIS</td>
<td>Time History of Events and Macroscale Interactions during Substorms mission</td>
</tr>
<tr>
<td>( u )</td>
<td>Velocity (in 6D phase space)</td>
</tr>
<tr>
<td>ULF</td>
<td>Ultra-low frequency - ( \lesssim 10 ) Hz</td>
</tr>
<tr>
<td>USGS</td>
<td>United States Geological Survey</td>
</tr>
<tr>
<td>UT</td>
<td>Universal time</td>
</tr>
<tr>
<td>( v )</td>
<td>Velocity</td>
</tr>
<tr>
<td>( V )</td>
<td>Electric Potential</td>
</tr>
<tr>
<td>( v_A )</td>
<td>Alfvén speed</td>
</tr>
<tr>
<td>( v_E )</td>
<td>( \mathbf{E} \times \mathbf{B} ) drift</td>
</tr>
<tr>
<td>( v_F )</td>
<td>General force drift</td>
</tr>
<tr>
<td>( W_f(t, f) )</td>
<td>Morlet wavelet transform of function ( f(t) )</td>
</tr>
<tr>
<td>( x )</td>
<td>Position (in 6D phase space)</td>
</tr>
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<td>( Z )</td>
<td>Charge state</td>
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</table>
1. Introduction

The magnetosphere is the space plasma environment around the Earth, formed by the interaction of the solar wind with the geomagnetic field. This complex interaction is not only of fundamental interest in understanding the plasma state and its associated processes, but can also have significant impacts on both space-based and terrestrial assets, with commercial and societal consequences.

In chapter 2, the fundamental properties of the plasma state are introduced as well as the various methods of modelling them mathematically. These methods lead to a number of wave modes and discontinuities that will prove to be important in this thesis. The average properties of the magnetosphere are described in chapter 3, highlighting the various regions and boundary layers. Of these, the magnetosheath is particularly of note as this region acts as the interface between the solar wind and the magnetospheric boundary, the magnetopause. While the general properties of the magnetosphere under various upstream conditions have been known fairly well for a long time, the system is highly dynamic. This is because the solar wind conditions are always changing, with variations in the upstream pressure and magnetic field direction occurring on timescales of generally a few minutes. Therefore, transient processes and phenomena, the subject of chapter 4, are of importance. This thesis focusses on one such transient phenomenon, namely large amplitude pulses in the magnetosheath dynamic pressure, and their understood properties and potential origins are described in this chapter as well as many of the outstanding questions surrounding them.

The aim of this thesis is to further the understanding of the origins, occurrence, properties and impacts of these dynamic pressure transients in the magnetosheath. Such work necessitates the use of multipoint observations and the five THEMIS spacecraft are therefore an invaluable resource in this respect. A description of these spacecraft and their instrumentation as well as those of ACE, WIND and GOES are given in chapter 5 along with the other assets (ground magnetometer...
and radar networks) used in this thesis.

In chapter 6 a case study of magnetosheath pressure pulses is presented, showing simultaneous observations of the pristine solar wind, foreshock and magnetosheath during periods of dynamic pressure pulses. These prove that no similar dynamic pressure variations existed upstream of the bow shock and that the majority of pulses were downstream of the quasi-parallel shock. By considering previously suggested mechanisms for their generation, it is shown that the pressure pulses could not be caused by reconnection, hot flow anomalies, or short, large-amplitude magnetic structures and that at least some of the pressure pulses appeared to be consistent with previous simulations of solar wind discontinuities interacting with the bow shock.

The first comprehensive statistical study of dynamic pressure pulses in the magnetosheath is presented in chapter 7, revealing their occurrence about 2% of the time and their predominant origin near the quasi-parallel bow shock. The results suggest that a stable foreshock and hence foreshock structures or processes may be important in the generation of the majority of magnetosheath dynamic pressure pulses. The typical properties of the pulses are presented, which show that the total pressure is enhanced in these structures, generally by a factor of $\sim 2$, thus they have the potential to have effects within the magnetosphere.

These effects are studied in chapter 8, continuing the case study of chapter 6 by utilising a comprehensive chain of observations from the magnetopause to the ground. It is found that the response to pulses is much smoother than the sharp, impulsive pressure variations, thus the magnetopause acts like a low pass filter suppressing timescales shorter than a few minutes. Ground magnetometer and radar data along with equivalent ionospheric currents show signatures of travelling convection vortices, similar to the response from pressure variations of solar wind origin. However, the signatures are associated with groups of magnetosheath pulses rather than individual ones. Thus the scale-dependent magnetospheric response to these transient pressure variations, results in coherent signatures on longer timescales than any individual pulse.

Finally, chapter 9 summarises the results of this thesis and discusses the remaining questions surrounding the dynamic pressure pulses in the magnetosheath.
More than 99% of all visible matter is in the plasma state. Plasmas are quasi-neutral gases consisting of positively and negatively charged particles (usually ions and electrons) which are subject to electric, magnetic and other forces, and which exhibit collective behaviour. In this chapter the ways of mathematically modelling this state are described along with important concepts that arise which will underlie the work in this thesis. Most of this information can be found in introductory text books [e.g. Baumjohann and Treumann, 1997].

2.1. Definition of a Plasma

There are loosely three criteria which define the plasma state, the first of which is the “plasma approximation”. This states that charged particles must be close enough together such that each particle influences many nearby charged particles and not simply the closest one. This criterion can be characterised mathematically by considering the influence of a single positive charge $q$ on a plasma. This positive charge will attract electrons, which have much smaller mass than protons, and will thus shield it from the surrounding charged particles of the plasma. However since electrons have non-zero thermal energy, this shielding will not be totally effective and the electric potential at a distance $r$ away from the charge will be given by

$$V = \frac{q}{4\pi \varepsilon_0 r} \exp \left( -\frac{r}{\lambda_D} \right)$$  \hspace{1cm} (2.1)

where $\lambda_D$ is called the Debye length, defined as

$$\lambda_D = \sqrt{\frac{\varepsilon_0 k_B T_e}{n_e e^2}}$$  \hspace{1cm} (2.2)
where $T_e$ is the electron temperature in Kelvin (note that sometimes temperatures are expressed in terms of the electronvolt eV, where $T[eV] = T[K]k_B/|e|$) and $n_e$ is the electron number density. The Debye length is thus the e-folding distance over which positive charges are shielded by electrons. Therefore, the “plasma approximation” is valid when the number of charge carriers within the Debye sphere (a volume of radius $\lambda_D$) is large, hence collective behaviour occurs. Over scales larger than the Debye length the plasma can be considered quasi-neutral.

The second criterion of the plasma state is that the Debye length must be short compared to the physical size of the plasma. This means that interactions in the bulk of the plasma are more important than edge effects.

The final criterion relates to the electron plasma (angular) frequency $\omega_{pe}$, a natural frequency related to plasma oscillations. These are rapid electrostatic oscillations of the electron density: if electrons are displaced then an electric field is generated due to the charge separation, causing a restoring force which results in simple harmonic motion at a frequency

$$\omega_{pe} = \sqrt{\frac{n_e e^2}{m_e \varepsilon_0}}$$

(2.3)

for “cold” electrons. In this limit the oscillations are dispersionless and non-propagating, however, when the electrons’ thermal speed is also considered the oscillations are weakly modified introducing dispersion

$$\omega^2 = \omega_{pe}^2 + 3k^2 \frac{k_B T_e}{m_e}$$

(2.4)

where $\omega$ is the wave angular frequency and $k$ is the wavenumber. This equation describes propagating waves of electron oscillations known as Langmuir waves. The plasma criterion related to the plasma frequency requires this quantity to be large compared to the electron-neutral collision frequency, such that electrostatic interactions dominate over the processes of ordinary gas kinetics.
2.2. Single Particle Motion

The simplest approach of modelling plasmas treats all the individual particles as independent of one another with their effects on the magnetic field $\mathbf{B}$ or electric field $\mathbf{E}$ neglected. This is only applicable in the most rarified plasmas, where collective effects are negligible, with strong external magnetic fields. In this case, the velocity of each particle $\mathbf{v}$ is determined by the Lorentz force

$$m \frac{d\mathbf{v}}{dt} = q (\mathbf{E} + \mathbf{v} \times \mathbf{B})$$ \hspace{1cm} (2.5)

where $m$ and $q$ are the particle’s mass and charge respectively. When $\mathbf{B}$ is constant and $\mathbf{E}$ is zero, particles will gyrate about magnetic field lines (see Figure 2.1a) with an angular frequency

$$\Omega_g = \frac{qB}{m}$$ \hspace{1cm} (2.6)

known as the gyrofrequency (or cyclotron frequency), with a gyroradius (or Larmor radius)

$$r_g = \frac{v_\perp}{|\Omega_g|}$$ \hspace{1cm} (2.7)

where $v_\perp$ is the component of the velocity perpendicular to the magnetic field. Along the direction of the magnetic field particles move at constant speed, resulting in a helical trajectory. This trajectory is defined by the particle’s pitch angle, the angle between the particle’s velocity vector and the local magnetic field such that a pitch angle of $0^\circ$ represents a particle travelling along the magnetic field direction, $180^\circ$ corresponds to anti-parallel motion and $90^\circ$ is associated with pure gyromotion.

In many cases of the single particle treatment of a plasma, the full motion of particles can be considered as the superposition of a relatively fast gyromotion about a point called the guiding centre and a relatively slow drift of this point. The drift speeds may differ for various species depending on their charge states, masses, or temperatures, possibly resulting in electric currents or chemical separation.
Since the magnetic force on charged particles is always perpendicular to the magnetic field, it has no influence on the parallel motion. Thus if there is a constant electric field parallel to the magnetic field, then the particles will accelerate along the field lines. However, an electric field component perpendicular to the magnetic field causes a drift of the guiding centre at a constant velocity, known as the $E \times B$ drift, given by

$$v_E = \frac{E \times B}{B^2}$$  \hspace{1cm} (2.8)

which is perpendicular to both $E$ and $B$. This is charge independent, as illustrated in Figure 2.1b. Equation 2.8 can be generalised to any force $F$ yielding a drift

$$v_F = \frac{F \times B}{qB^2}$$  \hspace{1cm} (2.9a)

$$= \frac{1}{\Omega_g} \left( \frac{F}{m} \times B \right)$$  \hspace{1cm} (2.9b)

as shown in Figure 2.1c.
2.3. Kinetic Theory

The most “exact” way to specify the state of a plasma is to give the time dependent positions $x(t)$ and velocities $v(t)$ of all particles, determined by their equations of motion i.e. the Lorentz force. The electric and magnetic fields are those generated by all the particles in the plasma, which satisfy Maxwell’s equations:

1. $\nabla \cdot \mathbf{E} = \rho_c/\epsilon_0$ \hspace{1cm} (2.10a)
2. $\nabla \cdot \mathbf{B} = 0$ \hspace{1cm} (2.10b)
3. $\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$ \hspace{1cm} (2.10c)
4. $\nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t}$ \hspace{1cm} (2.10d)

where $\rho_c$ is the charge density and $\mathbf{j}$ is the current density. However solving this is a difficult task given the massive number of particles usually under consideration, even in the most rarified of plasmas.

Given that plasmas behave collectively, it is not necessary to follow individual particles. Therefore one can ensemble average over all microstates, yielding a 6-dimensional phase space density $f_s(x,u,t)$ for each species. This specifies the number of particles of species $s$ with positions between $x$ and $x + dx$ and velocities between $u$ and $u + du$ at time $t$. Thus the total number of particles (of all species) in the system $N$ is given by

$$N = \sum_s \int d^3 x \int d^3 u f_s(x,u,t)$$ \hspace{1cm} (2.11)

The evolution of this 6D phase space density is governed by the kinetic equation

$$\frac{\partial f}{\partial t} + u \cdot \nabla_x f + \frac{q}{m} (\mathbf{E} + \mathbf{u} \times \mathbf{B}) \cdot \nabla_u f = \left( \frac{\partial f}{\partial t} \right)_c$$ \hspace{1cm} (2.12)

where $\nabla_x$ denotes derivatives in space, $\nabla_u$ derivatives in velocity and the right hand side is Boltzmann’s collision term which can be estimated in a number of ways (this
approximation neglects correlations between the fields. Space plasmas, however, are often collisionless and therefore the right hand side of Equation 2.12 is often set to zero resulting in the simplest possible form of the kinetic equation of a plasma, the Vlasov equation [Vlasov, 1938, 1968]. The kinetic (or Vlasov) equation is coupled to Maxwell’s equations (Equation 2.10) through the fields and since both $\rho_c$ and $\mathbf{j}$ depend on $f_s$ the whole system is a complicated non-linear 6-dimensional problem. Thus kinetic descriptions of a plasma, whilst encapsulating all the relevant physical processes and scales, are difficult both analytically and computationally.

### 2.4. Fluid Theory

There are many approximations to the kinetic equations to make the system easier to solve. One is to take velocity moments of the distribution function yielding macroscopic variables such as number density of species $s$

$$n_s(x, t) = \int d^3u f_s(x, u, t)$$

(2.13)

bulk velocity

$$v_s(x, t) = \frac{1}{n_s} \int d^3u f_s(x, u, t) u$$

(2.14)

and the thermal pressure tensor

$$P_s(x, t) = m_s \int d^3u f_s(x, u, t) (u - v_s) \otimes (u - v_s)$$

(2.15)

which describes the spread of particle velocities about the bulk velocity. The evolution of these macroscopic variables is determined by taking velocity moments of Equation 2.12. This approach is valid as long as typical length scales are much longer than the particle gyroradius and time scales are much longer than the ion gyration period.
2.4 Fluid Theory

2.4.1. Multi-Fluid Equations

Braginskii [1965] originally derived the fluid equations keeping the multiple species separate. Since the \( n \)th moment of the kinetic equation will always involve the \((n + 1)\)th moment of the distribution function, a closed set of equations cannot be obtained without further assumptions. One way of closing the equations is to impose an equation of state on the plasma i.e. an energy relationship. The ideal gas equation with isotropic pressure \( P_s = n_s k_B T_s \), where \( T_s \) is the temperature, is often used since it is valid in the plasma approximation and the equation of state is chosen depending on what kind of process is being investigated [e.g. Koskinen, 2010]. For instance when changes are slow the isothermal approximation can be used (constant temperature), since the plasma has sufficient time to redistribute energy in order to maintain thermal equilibrium. If changes happen more quickly than heat can be transferred, an adiabatic equation of state can be used, with adiabatic index \( \gamma \) often taken as 5/3, such that the multi-fluid equations are (assuming no recombination or ionisation)

\[
\frac{\partial n_s}{\partial t} + \nabla \cdot (n_s \mathbf{v}_s) = 0 \tag{2.16a}
\]

\[
n_s m_s \left( \frac{\partial}{\partial t} + \mathbf{v}_s \cdot \nabla \right) \mathbf{v}_s = n_s q_s (\mathbf{E} + \mathbf{v}_s \times \mathbf{B}) - \nabla P_s + \mathbf{R}_s \tag{2.16b}
\]

\[
\left( \frac{\partial}{\partial t} + \mathbf{v}_s \cdot \nabla \right) \left( \frac{P_s}{n_s} \right) = 0 \tag{2.16c}
\]

where Equation 2.16a is the continuity equation, Equation 2.16b is the momentum equation with \( \mathbf{R}_s \) being the rate of increase of momentum due to collisions, and Equation 2.16c is the adiabatic equation of state.

2.4.2. Magnetohydrodynamics (MHD)

A further approximation is to consider the plasma as a single conducting fluid. This is called magnetohydrodynamics (MHD), which can be derived by combining the
multi-fluid equations for the different species e.g. ions and electrons

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \tag{2.17a}
\]

\[
\rho \left( \frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla \right) \mathbf{v} = \mathbf{j} \times \mathbf{B} - \nabla P_{th} \tag{2.17b}
\]

\[
\mathbf{E} + \mathbf{v} \times \mathbf{B} = \frac{\mathbf{j}}{\sigma} + \frac{\mathbf{j} \times \mathbf{B}}{n_e} - \nabla P_e \tag{2.17c}
\]

\[
\left( \frac{\partial}{\partial t} + \mathbf{v}_s \cdot \nabla \right) \left( \frac{P_{th}}{\rho^\gamma} \right) = 0 \tag{2.17d}
\]

where \( \rho = m_i n_i + m_e n_e \) is the total mass density, \( \mathbf{v} = (m_i n_i \mathbf{v}_i + m_e n_e \mathbf{v}_e)/\rho \) is the centre of mass velocity, \( P_{th} = P_i + P_e \) is the total (isotropic) thermal pressure and \( \sigma \) is the (isotropic) conductivity. Thus MHD consists of the continuity equation (Equation 2.17a), momentum equation (Equation 2.17b), an Ohm’s law (Equation 2.17c) where the last two terms on the right hand side are often ignored, equation of state (Equation 2.17d), Faraday’s law (Equation 2.10c) and Ampère’s law (Equation 2.10d) where the displacement current is neglected (since speeds are typically \( \ll c \)).

Using Ampère’s law, the \( \mathbf{j} \times \mathbf{B} \) force in the momentum equation can be written as

\[
\mathbf{j} \times \mathbf{B} = -\nabla \left( \frac{B^2}{2\mu_0} \right) + \frac{1}{\mu_0} (\mathbf{B} \cdot \nabla) \mathbf{B} \tag{2.18}
\]

where \( B^2/2\mu_0 = P_B \) is the magnetic pressure, identical to any other physical pressure except that it is carried by the magnetic field rather than by the kinetic energy of the plasma’s constituent particles. The second term on the right hand side of Equation 2.18 is the magnetic tension force, analagous to the tension in rubber bands and their restoring force, which acts to straighten field lines.

Manipulating Faraday’s law and Ohm’s law leads to the MHD Induction Equation

\[
\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \frac{1}{\mu_0 \sigma} \nabla^2 \mathbf{B} \tag{2.19}
\]

where the two terms on the right hand side represent convection and diffusion of
the magnetic field respectively. A useful dimensionless number in comparing the relative effects of these is the magnetic Reynolds number

\[
R_m = \frac{\text{convection}}{\text{diffusion}} = \left| \frac{\nabla \times (\mathbf{v} \times \mathbf{B})}{\nabla^2 \mathbf{B}/\mu_0 \sigma} \right| \approx \frac{vB/l}{B/\mu_0 \sigma l^2} \approx \mu_0 \sigma vl
\]  

where \( l \) and \( v \) represent typical length and velocity scales of the plasma. If \( R_m \gg 1 \), typical for most space plasmas, the diffusive term can be ignored and the fluid can be treated as a perfect conductor. This approximation (along with \( l \gg c/\omega_{pe} \) the plasma skin depth to which electromagnetic radiation can penetrate) is known as Ideal MHD, where the right hand side of Equation 2.17c goes to zero. In this regime, it can be shown [e.g. Schwartz et al., 2004] that the rate of change of magnetic flux passing through a surface \( S \)

\[
\frac{d}{dt} \int_S d\mathbf{S} \cdot \mathbf{B} = \int_S d\mathbf{S} \cdot \left( \frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B}) \right)
\]

is zero in the Ideal MHD limit and thus the magnetic flux threading the surface is constant [Alfvén, 1943]. This is known as the “frozen in” flux approximation and qualitatively means that a plasma parcel and the magnetic field threading it will move in unison, thus the magnetic field lines can be thought of as physical constructs tied to the plasma, as illustrated in Figure 2.2. Similarly, in multi-fluid theories the magnetic field can be thought of as tied to the electron fluid, rather than the bulk plasma, at length scales less than the ion inertial length \( d_i = c/\omega_{pi} \) (\( \omega_{pi} = \sqrt{n_i Z^2 e^2/m_i e_0} \) is the ion plasma frequency where \( Z \) is the charge state of the ions), the scale at which ions decouple from electrons. It should be noted that in the Ideal MHD limit, the right hand side of Equation 2.17c goes to zero and thus \( \mathbf{E} = -\mathbf{v} \times \mathbf{B} \) is known as the motional electric field.

Many of the interesting effects of plasmas are averaged out in deriving MHD from
Figure 2.2.: Illustration of the “frozen in” flux approximation. Under this approximation magnetic field lines (black lines), loci instantaneously following the magnetic field direction $\mathbf{B}$ (arrows along the lines) through space, are physically meaningful and are tied to the plasma hence move in unison with it. Therefore, a uniform horizontal field will be distorted due to the motion of the plasma $\mathbf{v}$, indicated by the grey arrows, resulting in the displayed field line pattern.

plasma kinetics. This is why hybrid simulations are sometimes performed [e.g. Lin et al., 1996b; Blanco-Cano and Russell, 2006], where the ion kinetics are treated in full but electrons are modelled as a neutralising fluid for simplicity.

2.5. Waves & Discontinuities in Plasmas

Fluid and kinetic models of plasmas support a wide variety of wave modes, both electromagnetic and electrostatic in nature. While the electrostatic Langmuir wave has already been mentioned, here for simplicity a discussion of only magnetohydrodynamic waves is presented. These are derived by making perturbations about an equilibrium state and linearising the MHD equations in these perturbations. Typically a stationary ideal homogeneous equilibrium is chosen with vanishing average velocity and electric fields, overall pressure equilibrium and vanishing magnetic stress. This
yields the velocity perturbation relation [e.g. Baumjohann and Treumann, 1997]

\[
\begin{pmatrix}
\omega^2 - v_A^2 k_\parallel^2 - c_{ms}^2 k_\perp^2 & 0 & -c_A^2 k_\parallel k_\perp \\
0 & \omega^2 - v_A^2 k_\parallel^2 & 0 \\
-c_A^2 k_\parallel k_\perp & 0 & \omega^2 - c_A^2 k_\parallel^2
\end{pmatrix}
\begin{pmatrix}
\delta v_x \\
\delta v_y \\
\delta v_\parallel
\end{pmatrix} = 0
\] (2.21)

where the background magnetic field \(B_0\) points in the \(\hat{e}_\parallel\) direction and the wave vector \(k = k_\parallel \hat{e}_\parallel + k_\perp \hat{e}_x\) has components both along the background field and a direction perpendicular to it. The relation in Equation 2.21 has been simplified by introducing a number of characteristic wave speeds: the sound speed \(c_s = \sqrt{\gamma P_0/\rho_0}\) similar to that in a regular fluid; the Alfvén speed \(v_A = \sqrt{B_0/\mu_0\rho_0}\) which depends on both the background magnetic field strength \(B_0\) and density \(\rho_0\); and the magnetosonic speed \(c_{ms}^2 = c_s^2 + v_A^2\).

### 2.5.1. Alfvén Waves

One of the solutions to Equation 2.21 relates to the Alfvén wave [Alfvén, 1942], which is formed of velocity fluctuations purely in the \(\hat{e}_y\) direction i.e. perpendicular to both the ambient magnetic field and the wave vector as illustrated in Figure 2.3. Alfvén waves follow the dispersion relation

\[
\omega^2 = v_A^2 k_\parallel^2
\] (2.22)

thus its phase velocity is \(v_A \cos \theta_{Bk}\), where \(\theta_{Bk}\) is the angle between the wavevector and background field direction, and its group velocity is \(\pm v_A \hat{e}_\parallel\) where the plus sign corresponds to parallel propagation (i.e. \(k \cdot B_0 > 0\)) and the minus sign to the anti-parallel case. It should be noted that even though the wave transports energy along the magnetic field direction, the wavevector may be at any angle to the field.

The fluctuations of the Alfvén wave are purely transverse and follow the so-called Walén relation [Walén, 1944]

\[
\frac{\delta v}{v_A} = \pm \frac{\delta B}{B_0}
\] (2.23)
Figure 2.3: Illustration of an Alfvén wave propagating (with wavevector $k$) parallel to the background magnetic field $B_0$. The magnetic field and velocity perturbations $\delta B$ and $\delta v$ are perpendicular to the background field and, in this case, opposite to one another. The restoring force of the Alfvén wave is the magnetic tension due to the bending of the field line, similar to waves on a string.

where the minus (plus) sign corresponds to the parallel (anti-parallel) propagating solution. Electric field perturbations are $\pm v_A |\delta B| \hat{e}_x$ and there are no density, pressure or magnetic field strength variations associated with this mode, thus the wave is incompressible and can be thought of as string-like oscillations of magnetic field lines due to the magnetic tension force.

2.5.2. Magnetosonic Waves

The two other solutions to Equation 2.21 are the magnetosonic waves (so called because they involve both the Alfvén and sound speeds) given by

$$\omega^2 = \frac{k^2}{2} \left( c_{ms}^2 \pm \sqrt{\left( v_A^2 - c_s^2 \right)^2 + 4 v_A^2 c_s^2 \frac{k_\perp^2}{k^2}} \right)$$

with the positive sign corresponding to the fast magnetosonic wave and the negative sign to the slow magnetosonic wave. Unlike Alfvén waves, these contain density and magnetic field strength variations (see Figure 2.4) and hence pressure variations. Magnetosonic waves can contain motions both parallel and perpendicular to the magnetic field (depending on the wavevector). While parallel velocity perturbations are connected to parallel thermal pressure variations, the perpendicular motions are connected with variations in the total (thermal plus magnetic) pressure. In the fast mode wave the thermal pressure variations are in phase with those of the magnetic pressure, amplifying the force on the plasma, but are they out of phase in the slow mode wave.

In the case of $k$ perpendicular to the background field, the two roots to the dispersion relation become $\omega = \pm c_{ms} k_\perp$ for the fast wave and $\omega = 0$ known as the entropy mode.
Figure 2.4.: Illustration of a magnetosonic wave propagating (with wavevector $k$) perpendicular to the background magnetic field $B_0$. The magnetic field perturbations $\delta B$ are along the background field direction whereas the velocity perturbations $\delta v$ are perpendicular to it. The magnetic field strength (and thus magnetic pressure) is modified by wave, shown both by the density of magnetic field lines (arrows) and the shading, where black and white corresponds to increased and decreased field strength respectively.

which is a non-propagating wave with no magnetic, velocity or pressure variations where only the density and temperature vary. For $k$ parallel to $B_0$ the roots are $\omega^2 = v_A^2 k_\parallel^2$ and $\omega^2 = c_s^2 k_\parallel^2$, where the character of the waves depends on whether $v_A$ or $c_s$ is higher. For $v_A > c_s$ the first of these is the fast mode wave which propagates at the Alfvén speed whereas the slow mode is simply a sound wave, thus not coupled to the magnetic field (and vice versa if $v_A < c_s$). At intermediate angles there is a smooth variation in phase velocities between the two limits described, as shown in the Friedrichs diagrams of Figure 2.5.

Figure 2.5.: Friedrichs diagrams for magnetosonic waves where the distance from the origin represents the phase speed of the different wave modes (pure Alfvén as well fast and slow magnetosonic waves) for a wavevector in that direction. These are shown where the Alfvén speed is greater than the sound speed ($v_A > c_s$, left) and where the Alfvén speed is less than the sound speed ($v_A < c_s$, right). The background magnetic field $B_0$ is directed upwards in both cases.
2.6. Shocks and discontinuities

As well as waves, plasmas can also exhibit transition layers where the properties change from one equilibrium state to another, called discontinuities or shocks. Using the conservative form of the MHD equations one can derive Rankine-Hugoniot jump conditions in the frame moving with the discontinuity/shock [e.g. Burgess, 1995]

\[
\begin{align*}
[rho n] &= 0 & (2.25a) \\
[B_n] &= 0 & (2.25b) \\
\left[ rho^2 n^2 + P_{th} + \frac{B^2 t}{2\mu_0} \right] &= 0 & (2.25c) \\
\left[ rho n v_t - \frac{B_t B_n}{\mu_0} \right] &= 0 & (2.25d) \\
\left[ \left( \frac{\gamma}{\gamma - 1} \rho^2 + \frac{v^2}{2} \right) \rho v_n + \frac{v_n B^2 t}{\mu_0} - \frac{B_n (B_t \cdot v_t)}{\mu_0} \right] &= 0 & (2.25e) \\
[(v \times B)_t] &= 0 & (2.25f)
\end{align*}
\]

where the square brackets denote the jump in the enclosed quantity when crossing the boundary and the subscripts \(n\) and \(t\) refer to the normal and tangential components of vectors with respect to the discontinuity/shock front. From these jump conditions it is possible to classify discontinuities and shocks.

Contact discontinuities (CDs) are transition layers across which there is no particle transport \((v_n = 0)\) and the thermal pressure, magnetic field and velocity are continuous with only the density and temperature changing (c.f. entropy waves). This temperature gradient, however, gets rapidly dispersed by electron heat flux along the magnetic field and, therefore, contact discontinuities are thought not to be particularly stable.

Tangential discontinuities (TDs) are surfaces of total pressure balance between two contacting plasmas with no mass or magnetic flux crossing the discontinuity. Therefore the normal to a tangential discontinuity can be given by

\[
n = \frac{B_u \times B_d}{|B_u \times B_d|} \quad (2.26)
\]
where $B_u$ and $B_d$ are the upstream and downstream magnetic fields. The density, thermal pressure and tangential component of the magnetic field vector can be discontinuous across the layer.

Shocks are transition layers across which there is a transport of particles and there are three types of shocks in MHD: slow mode, intermediate and fast mode shocks. Intermediate shocks are non-compressive (the plasma density is continuous) and a special case of these, referred to as rotational discontinuities (RDs), are isobaric and isentropic such that the only discontinuous quantity is the tangential component of the magnetic field which can “rotate”. Slow and fast mode shocks are compressive and are associated with an increase in entropy. Across the slow mode shock the tangential component of the magnetic field decreases whilst across the fast mode it increases. The type of shock depends on the relative magnitude of the upstream velocity in the frame moving with the shock with respect to some characteristic speed i.e. the slow and fast magnetosonic speeds, thus demonstrating a link between shocks and MHD wave modes. One example of a collisionless fast mode shock is the bow shock of Earth’s magnetosphere, which will be introduced in the next chapter.
3. The Terrestrial Magnetosphere

The following is an introduction and discussion of the average properties of the terrestrial magnetospheric system, with particular emphasis on the dayside and topics relevant to solar wind - magnetosheath - magnetosphere coupling. In chapter 4 the dynamical coupling between these regions is discussed.

3.1. The Solar Wind Near Earth

The solar wind is a continuous stream of plasma ejected from the upper atmosphere of the Sun which pervades interplanetary space. Its existence was first deduced from the properties of cometary tails by Biermann [1951], subsequently explained by Parker [1958] from the solutions to the fluid equations for the solar atmosphere and first measured in situ by Gringauz et al. [1960] and Snyder and Neugebauer [1966].

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Slow Wind</th>
<th>Fast Wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number density $n$</td>
<td>15 cm$^{-3}$</td>
<td>5 cm$^{-3}$</td>
</tr>
<tr>
<td>(95 protons, 5% alphas)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk velocity $v_{sw}$</td>
<td>350 km s$^{-1}$</td>
<td>600 km s$^{-1}$</td>
</tr>
<tr>
<td>Proton Temperature $T_p$</td>
<td>$5\times10^4$ K</td>
<td>$2\times10^5$ K</td>
</tr>
<tr>
<td>Electron Temperature $T_e$</td>
<td>$2\times10^5$ K</td>
<td>$8\times10^5$ K</td>
</tr>
<tr>
<td>Magnetic field strength $B$</td>
<td>6 nT</td>
<td>6 nT</td>
</tr>
</tbody>
</table>

Table 3.1.: Typical values of solar wind properties at 1 AU measured by Helios 2. Data from Bruno and Carbone [2005].

The solar wind is a tenuous gas, with Table 3.1 showing typical properties near Earth. Embedded within it are magnetic fields which originated in the solar atmosphere. Whilst the solar wind flows radially from the Sun, the solar rotation causes
the magnetic field lines to form a (“Parker”) spiral in space [Parker, 1958]. Since the equatorial rotation rate of the Sun is 25.4 days, the average angle of the magnetic field to the flow near Earth is \(\sim 45^\circ\). The sound and Alfvén speeds in the solar wind plasma are about 40 km s\(^{-1}\) at 1 AU, therefore the flow is supersonic and the plasma \(\beta\) (ratio of thermal and magnetic pressures) is typically around 1. The solar wind is essentially collisionless as the proton-proton collision time is \(\sim 4 \times 10^6\) s (the core electrons are not as collisionless, but on average proton-electron collisions only happen a few times between the solar corona and 1AU). Despite this collisionless nature, fluid approaches have proved quite successful in describing the macroscopic properties of the solar wind.

Contained within the solar wind are many magnetic, velocity and density fluctuations due to waves and discontinuities [e.g. Belcher and Davis Jr., 1971; Ness and Burlaga, 2001; Neugebauer, 2006]. The latter are often seen at time scales of 3 to 5 minutes, though similar discontinuities are seen at smaller time scales [Vasquez et al., 2007; Greco et al., 2010]. These changes in the interplanetary magnetic field (IMF) are mainly directional, with the relative proportion of RDs and TDs being affected by the source of the solar wind and the contribution of dynamical effects to its properties. All methods to reliably distinguish between the two require an estimate of the normal to the discontinuity and single spacecraft studies have typically used minimum variance analysis (MVA) to do so [e.g. Smith, 1973; Lepping and Behannon, 1980; Neugebauer et al., 1984]. MVA [Sonnerup and Cahill, 1967] relies on the divergence of \(\mathbf{B}\) being zero such that across a discontinuity boundary the component of the magnetic field normal to the boundary must remain constant. Thus MVA uses vector analysis of a number of samples through a discontinuity to determine the direction along which the variance in the field vectors is minimized (ideally it should be equal to zero). Smith [1973] defined four classes of discontinuity: rotational (RDs), tangential (TDs), “either” (EDs) and “neither” (NDs), which were classified by the fraction of magnetic field threading the discontinuity \(\mathbf{B} \cdot \mathbf{n}/B\) as well the size of the magnetic field change across the discontinuity \(\Delta |\mathbf{B}|/B\). Many studies [e.g. Burlaga and Ness, 1969; Horbury et al., 2001a; Knetter et al., 2004] have shown that the largest class of discontinuities are EDs. Knetter et al. [2004] compared normals determined from four spacecraft triangulation [Schwartz, 1998] to those from single spacecraft methods, namely MVA and the cross-product method (the theoretical normal of a TD given by \(\mathbf{n} = \mathbf{B}_u \times \mathbf{B}_d/|\mathbf{B}_u \times \mathbf{B}_d|\)). They found that the cross-product normals agreed fairly well with those from triangulation, however...
there were strong deviations between the MVA normals. Considering the plasma jump conditions in addition to the magnetic field change fails to clearly separate the discontinuities between RDs and TDs [Neugebauer, 2006].

The discontinuities and waves embedded within the solar wind change the conditions upstream of the Earth, most notably the orientation of the IMF. These variations away from the average solar wind conditions, over a number of different time scales, can have effects on Earth’s magnetosphere upon which the solar wind impacts.

### 3.2. The Magnetosphere

It has been known for several hundred years that the Earth possesses a magnetic field, indeed Gauss and Weber found that the field at the surface of the Earth is almost entirely dipolar, with a dipole moment of about $8 \times 10^{15}$ T m$^3$ tilted roughly $11^\circ$ from the rotation axis. This field acts as an obstacle to the solar wind as the respective magnetic fields are “frozen in” to the plasmas due to their high electrical conductivities, as explained in subsection 2.4.2. The solar wind exerts pressure on the Earth’s magnetic field thereby confining it to a cavity surrounding the planet: the magnetosphere [Chapman and Ferraro, 1930, 1931; Dungey, 1954, 1955]. The size of this cavity is determined by pressure balance at the boundary, called the magnetopause. Across the magnetopause the magnetic field usually undergoes a sharp change in both strength and direction, thus a sheet of electrical current flows in this plasma interface called the Chapman-Ferraro or Magnetopause current (see Figure 3.1 for this and further magnetospheric current systems). The position of the magnetopause at the nose can, to first order, be calculated by balancing the solar wind pressure (dominated by the dynamic or ram pressure $P_{dy\text{m}} = \rho v^2$ which is a momentum flux exerted on a body moving through a fluid medium, with the magnetic and thermal pressures only constituting $\sim1\%$) with that of the magnetosphere (principally magnetic pressure due to the small $\sim1$ cm$^{-3}$ densities of the outer magnetosphere [e.g. Lee, 1996]):

\[
\rho_{sw} v_{sw}^2 = B_{sph}^2 / 2\mu_0
\]

where the subscripts $sw$ and $sph$ refer to the solar wind and magnetosphere respectively. Whilst dependent on the upstream pressure, the magnetopause stand off
Figure 3.1.: Three-dimensional cutaway view of the magnetosphere. The light blue outer surface is the magnetopause, its boundary layers are shown in darker blue. Magnetic field lines are shown in blue, electric currents in yellow. The polar region where the magnetic field lines converge is the polar cusp. The bow shock has been omitted for clarity. [From De Keyser et al., 2005]

The distance is typically 10 \( R_E \) with a standard deviation of roughly 2 \( R_E \) [Kivelson and Bagenal, 1998].

Measurements by spacecraft have established the frequent presence of a plasma boundary layer immediately Earthward of the magnetopause [e.g. Eastman et al., 1976; Sckopke et al., 1981]. This magnetospheric boundary layer (blue areas in Figure 3.1) can be divided into three regions: the plasma mantle, exterior cusps and low-latitude boundary layer (LLBL).

### 3.2.1. The Ionosphere

Earth’s upper atmosphere is partly (0.1% or less) ionised at altitudes of 70-1500 km due to solar ultra-violet and X-ray radiation, charged particle precipitation and cos-
mic rays [e.g. Ratcliffe, 1972]. This region, the ionosphere, is coupled both to the neutral atmosphere and the magnetosphere. The distribution of plasma is dependent on latitude and local time in addition to being dependent on altitude, in part due to the day/night cycle. The magnetospheric coupling is due to the ionosphere’s electrical conductance, allowing interaction with the magnetosphere through electromagnetic and kinetic processes. One important magnetospheric coupling is the closure of field aligned currents (see Figure 3.1) in the ionosphere. While at low latitudes the ionospheric plasma is co-rotating with the Earth, at higher latitudes it is convecting under the influence of the large scale magnetospheric electric field mapped to low altitudes [Vasyliunas, 1970]. In this thesis, the ionosphere is mostly important in terms of its dynamical coupling with the magnetosphere, which is discussed in the next chapter.

3.2.2. The Plasmasphere

The plasmasphere is a torus of cold (less than 10 eV), dense (tens to thousands of particles per cubic centimetre [Park et al., 1978]) plasma outside the upper ionosphere, occupying the inner magnetosphere (blue region in Figure 3.1) typically out to a L-shells of 4-5 R_E (see Appendix B for the definition of L-shell). It is populated by the diffusive outflow of ionospheric plasma along mid- and low-latitude magnetic field lines, with an ion composition consisting primarily of protons with singly ionised Helium accounting for \(\sim 20\%\) of the number density [Horwitz et al., 1990]. The size, shape and dynamics of the plasmasphere vary strongly depending on the level of magnetospheric activity [e.g. Chappell et al., 1970]. During periods of low activity, the plasmasphere can become saturated with upflowing ionospheric plasma extending to L-shells of 6 or beyond until a diffusive equilibrium is reached. On the other hand, when the magnetosphere is disturbed, enhanced convection can erode the outer plasmasphere transporting plasma sunward towards the outer magnetosphere. This causes a steep drop in the density, by as much as two orders of magnitude over 0.5 R_E, known as the plasmapause which marks the outer boundary of the plasmasphere.
3.3. The Bow Shock

The magnetosphere acts as a blunt obstacle to the solar wind flow which consequently is slowed down and, to a large extent, deflected around it. Since the solar wind is supermagnetosonic, a bow shock wave is generated thermalising a substantial fraction of the particles’ kinetic energy thereby decreasing it to sub-magnetosonic speeds. The bow shock divides the solar wind flow into two regions: the undisturbed solar wind upstream and the disturbed magnetosheath flow downstream. It is a fast magnetosonic shock, since the solar wind is a high magnetosonic Mach number stream with \( M_{ms} \sim 8 \) on average, and is the best known and most studied example of a collisionless plasma shock and therefore has been the subject of extensive observational and theoretical investigations [e.g. Tsurutani and Stone, 1985].

A schematic view of the average location and shape of the bow shock is shown in Figure 3.2. The standoff distance of the bow shock \( r_{bs0} \) scales approximately linearly to that of the magnetopause \( r_{mp0} \) [Farris and Russell, 1994]

\[
r_{bs0} = \left( 1 + 1.1 \frac{(\gamma - 1) M_{ms}^2 + 2}{(\gamma + 1)(M_{ms}^2 - 1)} \right) r_{mp0}
\]

resulting in a typical position of the bow shock nose of 14 R_E, but this is highly variable. A number of statistical models of the bow shock position exist [e.g. Farris et al., 1991; Peredo et al., 1995] and the normals from such models have been shown to be in good agreement (to within 10°) with those derived from Cluster timings of well defined (typically quasi-perpendicular) shock crossings [Horbury et al., 2001a, 2002], which were remarkably stable under a wide range of upstream conditions and even whilst the shock was in rapid motion.

The nature of the shock transition depends primarily on two parameters. One is the Mach number of the shock wave, ranging from \( \sim 3-10 \), which is calculated from the solar wind velocity component normal to the shock. Consequently the bow shock forms a spatially restricted shield in front of the magnetosphere and undergoes a transition from a high-Mach number shock at its nose to a low Mach number shock at its flanks [e.g. Spreiter et al., 1966; Fairfield, 1971]. The other crucial parameter is the angle \( \theta_{Bn} \) between the upstream magnetic field direction and the local normal to the shock surface [Greenstadt, 1991]. Across the surface of the bow shock for the Parker spiral form of the IMF as depicted in Figure 3.2, \( \theta_{Bn} \) ranges from quasi-
Figure 3.2.: Schematic of Earth’s bow shock. The magnetic field - shock normal angle $\theta_{Bn}$ changes (for the average direction shown here) from quasi-parallel on the dawn side to quasi-perpendicular on the dusk side. The scales of the shock transition and dissipation regions are significantly different for the quasi-perpendicular and quasi-parallel cases as illustrated by the insets showing the evolution of the magnetic field magnitude measured by Cluster across two shock transitions. [From Balogh et al., 2005]
perpendicular on the dusk side, where the shock transition tends to be abrupt in
time in the frame of the solar wind and spatially well defined; to quasi-parallel
on the dawn side, where the transition occurs over an extended region containing
inhomogeneous and transient field and shock-related particle features. The reasons
for these differences are intimately tied to the physical processes of the foreshock
described in the next section. Of course the structures embedded in the solar wind
mean the conditions upstream of the bow shock are highly variable on a range of
spatial scales relative to the dimensions of the bow shock, which change the geometry
(quasi-parallel vs. quasi-perpendicular) and Mach number of the shock accordingly
over timescales of typically a few minutes.

The bow shock exhibits non-stationary processes, though the extent of these remains
an open question. Indications of non-stationarity have been found in low frequency
oscillations of the ion flux [Vaisberg et al., 1984, 1986a, b]; kinetic hybrid simulations
[Leroy et al., 1981, 1982] showing temporal variations of shock structure such as
the maximum value of the magnetic field; proposed models [Krasnosel’skikh, 1985;
Galeev et al., 1988] of non-linear effects over dispersion and dissipation, including
observed non-stationary whistler wave (right-handed electromagnetic electron waves
at frequencies \( \Omega_{gi} < \omega < \Omega_{ge}/2 \)) trains [Krasnosel’skikh et al., 1991]; rippling of the
shock surface from 2-dimensional hybrid [Lowe and Burgess, 2003] and full particle
simulations [Lembège and Savoini, 1992] (for a number of shock crossings an upper
limit on the scale of these ripples has been set by the Cluster separation scale due
to the agreement of shock orientations with the Peredo et al. [1995] model [Horbury
et al., 2001a, 2002], whereas a particularly slow encounter with the bow shock by
Cluster revealed ripples of wavelength 1000-2000 km [Moullard et al., 2006]); and
the cyclic self-reformation of the shock front [Lembège and Dawson, 1987; Lefebvre
et al., 2009]. Most results indicate that the characteristic timescale of the shock
front variations is of the order of one ion gyroperiod or less, related either to the
whistler mode expected to dominate the overall transition and/or the overturning
due to non-steady ion reflection.

3.4. The Foreshock

Although the bow shock primarily mediates the flow of the supermagnetosonic solar
wind, it also acts as a site for particle acceleration. It can act as a potential barrier
3.4 The Foreshock

and, for certain IMF geometries, a portion of the inflowing charged particles peculiarly reflect upstream rather than being processed by the shock and convecting downstream. Energetic magnetosheath particles can potentially “leak” upstream also [Schwartz et al., 1983]. The region of space upstream of the bow shock, magnetically connected to the shock and filled with backstreaming particles from it is known as the foreshock [e.g. Eastwood et al., 2005]. Since the charged particles are gyrating around the local magnetic field, they can only travel against the solar wind stream significantly if they are highly energetic compared with the solar wind beam and if $\theta_{Bn}$ is small, otherwise they are lost in the shock. This means that for the quasi-perpendicular bow shock the foreshock is restricted to the shock foot whilst in the quasi-parallel part it covers a much larger domain. Figure 3.3 illustrates this basic structure of the terrestrial foreshock, however the solar wind velocity and shock normal at the point the magnetic field intersects the shock are not a priori coplanar hence this schematic is implicitly simplified. The bow shock - foreshock system is highly non-linear, with many complicated feedback mechanisms and it is by no means clear that changes to the upstream conditions, particularly the IMF orientation, causes proportional changes to large-scale foreshock structure. The system response time scales are not well known either [Eastwood et al., 2005].

At Earth’s bow shock ions are measured with energies up to several hundred keV [e.g. Paschmann et al., 1981] (c.f. the kinetic energy of a proton in the solar wind $\sim$1 keV) and electrons with energies up to several tens of keV [e.g. Fitzenreiter, 1995]. Such suprathermal particles are energetic enough to escape the shock and, if the upstream field is reasonably uniform, their guiding center motion consists of two parts: parallel motion along the magnetic field line $v_\parallel$ and cross-field drift $v_\perp = (E \times B_0)/B_0^2$. Since $E = -v \times B_0$, the cross field drift is always in the downstream sense and is simply the component of the solar wind flow perpendicular to the field, therefore it is the same for all particle species and energies. This implies that one observes particles with higher velocities further upstream of lower velocity ones, as they are able to travel further away from the shock before they have cross field drifted the same distance as the slower particles [Filbert and Kellogg, 1979], a time-of-flight effect called velocity dispersion. The combination of inflowing plasma and counterstreaming particles is subject to a number of plasma instabilities, leading to the generation of waves.

The first particles observed downstream of the tangent field line are electrons in what is called the electron foreshock (see Figure 3.3). No backstreaming ions are
 Chapter 3  

The Terrestrial Magnetosphere

Figure 3.3.:  Schematic view of the terrestrial shock/foreshock system. The solar wind flows from the left hand side and the bow shock is represented by the curved line (the magnetopause is not shown). The foreshock, largely upstream of the quasi-parallel shock and confined to the region of space behind the tangent field line, exhibits significant spatial structure. Just behind the tangent field line is the electron foreshock where only backstreaming electrons are observed. Behind the ion foreshock boundary, field-aligned backstreaming ion distributions are typically observed. Deeper in the foreshock, close to the quasi-parallel shock, diffuse backstreaming ion distributions are observed. Two-dimensional velocity space relief plots are used to represent the field-aligned (close to the ion foreshock boundary) and the diffuse (close to the quasi-parallel shock) ion distributions. In these two dimensional relief plots, the sharp peak corresponds to the solar wind. [From Treumann and Scholer, 2001]

found in this region. This is as expected from velocity dispersion, because even though the electrons at the bow shock are tens of times less energetic, they are significantly less massive than ions such that electron velocities are a few orders of magnitude greater than ion ones. The electrons themselves are also seen to be velocity dispersed, resulting in electron beams producing a bump-on-tail distribution function [Fitzenreiter et al., 1984]. The waves observed in this region are typically at the plasma frequency and its second harmonic, essentially Langmuir waves, which are often shifted up or down in frequency deep in the electron foreshock [Fuselier
There is a similar region of backstreaming ions (consisting of about 2% of the solar wind ions) called the ion foreshock, where it appears that the ions farthest upstream originate from the bow shock where $\theta_{Bn}$ is less than about 70°. This implies that the acceleration mechanism for ions is not efficient enough at larger $\theta_{Bn}$. A number of different ion distributions are observed in the ion foreshock, each with its own associated properties.

Field aligned beams, narrow peaks in velocity phase space, are typically observed near the leading edge of the ion foreshock whilst the further downstream (and therefore magnetically connected to an increasingly quasi-parallel shock) one measures, the more diffuse in velocity space the ions become [Gosling et al., 1978] (Figure 3.3 shows example distributions). The transition between these regions is gradual and an “intermediate” population with a “kidney-shaped” velocity distribution follows the peaked populations. Ultra-low frequency (ULF; $\lesssim 10$ Hz) waves, are observed in the presence of the intermediate and diffuse distributions [Russell and Hoppe, 1983], consequently there is a second boundary within the ion foreshock confining
the region of ULF wave activity known as the ULF foreshock. \cite{LeRussell1992} found the ULF foreshock boundary intersects the bow shock at $\theta_{Bn} \sim 50^\circ$ and is statistically characterised by a proton travelling along the field line at $1.4v_{sw}$. Diffuse ions and ULF waves cause the solar wind protons to pitch angle scatter and therefore slow and deflect the solar wind \cite{Cao2009, HuiShan2009}. Figure 3.4 summarises the observed hydromagnetic waves and ion populations.

Large-amplitude ($|\delta B|/B_0 \sim 1$), quasi-monochromatic, approximately 30 s period kinetic fast magnetosonic waves are frequently observed in the ULF foreshock \cite{HoppeRussell1983, Eastwood2005} (see Figure 3.5 for an example time series), being generated by the ion-ion right hand resonant beam instability \cite{Brinca1991}. Such waves are of interest not only as an example of fundamental wave-particle interaction in collisionless plasmas but they also cause large changes in the magnetic field direction at the bow shock surface and hence $\theta_{Bn}$, resulting in periodic changes in bow shock properties \cite{GreenstadtMellott1985}. They typically propagate $\sim 20-40^\circ$ from the local magnetic field \cite{HoppeRussell1983, Eastwood2002, Eastwood2003} in a sunwards direction at speeds close to the local Alfvén speed in the plasma frame \cite{Mazelle2003}, but are convected earthward into the shock by the faster solar wind flow and are often observed in the magnetosphere \cite[e.g.][]{Clausen2009}. This convection also reverses their sense of polarisation, which is usually right-handed in the plasma frame, so that they appear left-handed in the spacecraft frame (relative to the magnetic field). The waves are often nearly sinusoidal but can also have steepened edges, sometimes with attendant whistler waves. These variations appear to be associated with changes in the distribution of backstreaming ions \cite{Meziane2001, Mazelle2003, Meziane2004}. Whereas the direction of the IMF controls whether waves are generated upstream of the shock or not, its strength controls the peak frequency at which waves are generated. \cite{Takahashi1984} found the dependence of this peak frequency $f_{UW}$ of upstream waves observed inside the dayside magnetosphere on the IMF strength $B_0$ and the cone angle $\theta_{Bx}$ (the angle ) to be in agreement with a simple model of wave generation by a cyclotron resonance of ions reflected at the bow shock:

$$f_{UW} \text{[mHz]} = 7.6B_0 \cos^2 \theta_{Bx}$$

(3.3)

Observational evidence supporting this is available in abundance from satellites in
3.4 The Foreshock

Figure 3.5.: Cluster observations of upstream ULF waves. (from top to bottom) ion energy spectrograms for “solar wind sectors” and “dusk”, magnetic field components and strength, ion density and bulk velocity components. [From Mazelle et al., 2003]
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The Terrestrial Magnetosphere

the solar wind [e.g. Le and Russell, 1992], the dayside magnetosphere [e.g. Arthur and McPherron, 1977] and ground-based magnetometers [e.g. Webb and Orr, 1976] as well as simultaneous observations of the waves in the foreshock, the magnetosphere and on the ground [Clausen et al., 2009].

Short large amplitude magnetic structures (SLAMS) [Schwartz et al., 1992] are often observed upstream of the quasi-parallel shock. The exact nature of SLAMS formation is still unknown, though they might be produced by electromagnetic ion/ion beam instabilities [e.g. Hellinger and Mangeney, 1999], a nonlinear interaction between gradients of suprathermal ions [e.g. Giacalone et al., 1993] or the steeping of upstream ULF waves [e.g. Schwartz et al., 1992]. These discrete structures, somewhat separated from surrounding fluctuations, are characterised by brief (5-20 s), large enhancements (\( \gtrsim 4 \) times) in the magnetic field strength and density. They propagate upstream in the solar wind frame and decrease the velocity of the solar wind plasma [Longmore, 2005]. SLAMS were thought to be distributed over a transition region of 2-3 R_E, as shown in Figure 3.6, however results from Cluster suggest this is much smaller at \( \sim 2500 \) km with individual scale sizes of 700-1000 km [Lucek et al., 2004a, 2008]. As they convect earthward their amplitude and phase speed increases [Omidi and Winske, 1990], slowing down relative to the Earth and merging with the shock. Thus the quasi-parallel shock is thought to consist of a “patchwork” of these structures [Schwartz and Burgess, 1991; Lucek et al., 2008].

3.5. The Magnetosheath

Downstream of the bow shock and upstream of the magnetopause lies the magnetosheath, formed mainly from decelerated and deflected solar wind but with a small contribution of plasma from the magnetosphere. Inherent in the magnetosheath plasma are both large scale spatial ordering, imposed by the shape of the magnetopause, and variability dependent on the solar wind input. The average properties of the magnetosheath have been studied by numerous spacecraft, with an example magnetosheath crossing by Cluster shown in Figure 3.7. The Rankine-Hugoniot relations for the fast mode bow shock, introduced in section 2.6, are largely consistent with the observed properties of magnetosheath plasma: density, temperature and magnetic field strength increase downstream of the shock, the plasma velocity drops to below the fast magnetosonic speed and is deflected such that the plasma flows...
3.5 The Magnetosheath

Figure 3.6.: Schematic of the relationship between SLAMS (ellipses), the magnetic field and bulk flow in the “patchwork” quasi-parallel shock. Note the appearance of steepened upstream edges of some SLAMS (black bars) and the SLAMS’ deceleration, deflection and merging as they convect toward, and become, the downstream state. [From S. J. Schwartz following Schwartz and Burgess, 1991]

around the blunt magnetosphere, reaching supersonic speeds again in the far flanks. However, it is expected that the nature of magnetosheath plasma properties are delicately coupled with bow shock parameters such as the shock geometry $\theta_{Bo}$, Mach number, cross-shock potential [e.g. Dimmock et al., 2012] and spatial scales within the shock transition [e.g. Bale et al., 2003; Schwartz et al., 2011]. Due to the highly complex and nonlinear nature of these processes, a complete understanding of how the upstream plasma properties impact the magnetosheath plasma does not exist [Dimmock and Nykyri, 2013].

The bow shock converts a substantial fraction of the solar wind’s kinetic energy into thermal (and magnetic) energy, the temperature increase for the solar wind ions being greater than for the electrons: the ion to electron temperature ratio in the magnetosheath is of order 6-7. The plasma $\beta$ shows large variations from order unity to much greater than one. Quasi-perpendicular collisionless shocks heat ions preferentially in the direction perpendicular to the background magnetic field [Gary et al., 1996] and ion reflection is important in this heating, especially at high
Mach shocks [Winske and Quest, 1988], leading to nonthermal, non-gyrotropic distributions near the shock. The magnetosheath develops a pronounced temperature anisotropy $T_\perp > T_\parallel$ behind the bow shock that increases toward the magnetopause due to wave-particle scattering, yielding a gyrotrropic, approximately bi-Maxwellian distribution [McKean et al., 1995]. As magnetosheath plasma approaches the magnetopause along the Sun-Earth line, it is further slowed until at the boundary there is no normal component of the velocity. Thus the solar wind dynamic pressure is converted across the magnetosheath into thermal and magnetic pressures, as shown in Figure 3.8. Note that the total magnetosheath pressure (thermal + dynamic + magnetic) is nearly, though not always exactly, equal to the solar wind pressure.

Early models employed Chapman-Ferraro theory combined with gas dynamics to describe magnetosheath properties [e.g. Spreiter et al., 1966], which neglect the magnetic and electric forces on the magnetosheath plasma. Since the bow shock...
3.5 The Magnetosheath

**Figure 3.8.** Results of an isotropic MHD simulation along the Sun-Earth line for northward (left) and radial (right) IMF, showing the thermal ($P$), magnetic ($P_b$) and dynamic ($P_{dyn}$) pressures. The total pressure corresponds to the upper boundary. [From Samsonov et al., 2013]

is a fast shock, the Rankine-Hugoniot relations imply that the magnetic field lines are refracted away from the shock normal. This, in addition to convection by the flow, drapes the field around the magnetopause (see Figure 3.9) and at the same time transports it downstream. Statistical studies of field line draping in the magnetosheath [Coleman, 2005; Longmore et al., 2006] have shown that the average clock angle (in the GSM $B_y$-$B_z$ plane perpendicular to the Sun-Earth line - see Appendix A for coordinate system definitions) in the magnetosheath reflects that of the IMF to within $\sim 30^\circ$ or less and are similar to model draping patterns but with statistically significant rotations consistent with the twisting of the magnetic field lines by the bulk plasma flow. Field line draping is expected to cause dawn-dusk asymmetries in the magnetosheath plasma at the magnetopause. Indeed Walsh et al. [2012] found that the proton density and temperature are greater on the dawn side while the magnetic field strenght and bulk flow are greater on the dusk side, with the results being largely consistent with the expected asymmetries from global MHD models under Parker spiral IMF.

For a more flow parallel direction of the IMF, draping mainly occurs on the quasi-perpendicular side due to the refraction, as seen in Figure 3.9. The draping compresses the field thereby increasing the magnetic pressure, breaking down the approximation of the gas dynamic model used in this instance. The enhanced magnetic pressure inside a compressed magnetosheath flux tube near the stagnation point will squeeze the magnetosheath plasma out of this tube into the flank-side magne-
Figure 3.9.: Flow deflection (grey streamlines) and magnetic field draping (black lines) in the magnetosheath from a Block-Adaptive-Tree-Solarwind-Roe-Upwind-Scheme (BATS-R-US) MHD simulation. The colour scale shows the number density. Adapted from figures by the CCMC.

tosheath in a process called plasma depletion [Zwan and Wolf, 1976]. It effectively dilutes the magnetosheath plasma near the nose below its theoretical density and is mainly observed when the magnetic fields in the magnetosheath and magnetosphere are nearly parallel i.e. northward IMF.

Fluctuations in the magnetic and plasma properties occur often in the magnetosheath and may be due to the intrinsic turbulence of the solar wind, passage of solar wind features [e.g. Gutynska et al., 2008], foreshock waves and non-linear structures convected downstream of the bow shock, fluctuations generated at the shock itself [e.g. Sckopke et al., 1983] and locally generated waves and instabilities. Variations can also be due to the radial gradient of the parameters combined with radial motion of the bow shock - magnetosheath - magnetopause system [e.g.
3.5 The Magnetosheath

Sibeck and Gosling, 1996]. The correlation length in the magnetosheath does not exceed ∼1 R_E for frequencies between 1-125 mHz [Gutynska et al., 2008] and does not depend significantly on the magnetic field or plasma flow direction, though it is increased during intervals of high speed solar wind, with high values of the IMF strength, if the amplitude of fluctuations is larger, and if solar wind structures persist on the background of magnetosheath fluctuations [Gutynska et al., 2008, 2009]. Generally the ion flux and magnetic field strength variations in the quasi-parallel magnetosheath are about 2 times larger and the magnetic field orientation 3 times more disturbed than in the quasi-perpendicular magnetosheath [Shevyrev et al., 2007]. The relative standard deviations of ion flux fluctuations also increase toward the magnetopause and with solar wind speed [Němeček et al., 2001]. In the quasi-parallel magnetosheath, magnetic field strength variations are uncorrelated with the ion flux, with the field parallel and perpendicular fluctuations having nearly the same power at all frequencies, whereas the quasi-perpendicular sheath exhibits an anti-correlation between the field and ion flux and perpendicular fluctuations dominated for high frequencies [Shevyrev et al., 2006].

![Figure 3.10.](image)

**Figure 3.10.:** Nearly sinusoidal, anticorrelated fluctuations of the magnetic field (solid) and ion density (dashed) associated with mirror modes observed in the magnetosheath. [From Leckband et al., 1995]

The anisotropic temperature of the magnetosheath plasma, particularly downstream of the quasi-perpendicular shock, can lead to the growth of both the electromagnetic proton cyclotron anisotropy instability (with magnetic fluctuations predominantly perpendicular to the background field) and the mirror instability (fluctuations mostly parallel to the field), with the field parallel plasma beta $\beta_\parallel$ parameterising
which has the faster growth rate: $\beta_\parallel < 1$ for the proton cyclotron instability and $\beta_\parallel > 1$ for the mirror instability [Gary et al., 1996]. Ion cyclotron waves are longitudinal oscillations of ions propagating almost perpendicular to the magnetic field with dispersion relation $\omega^2 = \Omega^2_g + k^2 c^2_s$ as a result of Lorentz, electrostatic, and ion pressure gradient restoring forces. They typically propagate away from their source region, whereas mirror modes are non-propagating in the plasma frame and are large amplitude, anti-correlated variations in the magnetic field magnitude and plasma density (see Figure 3.10) which can act as magnetic bottles, trapping part of the particle distribution [Kivelson and Southwood, 1996]. Narita and Glassmeier [2005] and Narita et al. [2006] found that waves transition from a mixture of electrostatic ion cyclotron waves and mirror modes in the outer magnetosheath to primarily mirror mode structures in the middle sheath. They also found an organisation in the wave propagation pattern, with magnetosheath waves generally propagating toward the flank region and the magnetopause.

Variations in the magnetosheath properties can potentially have implications on the magnetopause and within the magnetosphere. The understood dynamical coupling of the solar wind - magnetosheath - magnetosphere system is detailed in the next chapter.
Solar wind mass, energy and momentum can be transferred to Earth’s magnetosphere at the magnetopause. While chapter 3 presented typical magnetospheric conditions, transients are important due to the variability of the system and a variety of such phenomena have been observed at or near the magnetopause which can disturb the boundary and have effects within the magnetosphere. This chapter discusses some of these transients and their understood impacts upon the magnetosphere.

4.1. Reconnection

Magnetic reconnection is a process which occurs when the “frozen in” flux condition (introduced in subsection 2.4.2) breaks down, changing the topology of magnetic field lines. In thin boundary layers the magnetic Reynolds number can decrease to of the order of unity or below due to the small length scales, hence Ideal MHD can and does break down locally [Hughes, 1995]. An illustration of (basic x-line) reconnection is shown in Figure 4.1, where a thin current sheet separates regions of oppositely directed magnetic fields and there is a plasma inflow. This results in an x-type neutral line where the field vanishes which is surrounded by a diffusion region within which the magnetic Reynolds number is less than unity. Magnetic field lines entering the diffusion region from the two regions merge, or reconnect, with one another subsequently outflowing from the sides at the Alfvén speed. Thus the Walén relation [e.g. Walén, 1944; Sonnerup et al., 1981; Gosling et al., 2005] should hold for the vector velocity change when cutting through the exhaust i.e.

\[
v_2 - v_1 = \pm \left( \frac{\rho_1 [1 - \alpha P_1]}{\mu_0} \right)^{1/2} \left( \frac{B_2}{\rho_2} - \frac{B_1}{\rho_1} \right)
\]  

(4.1)
in the case of an anisotropic plasma where the subscripts 1 and 2 refer to either side of the current sheet and $\alpha_P$ is the pressure anisotropy factor

$$\alpha_P = \left(P_{th\|} - P_{th\perp}\right) \mu_0 / B^2$$

(4.2)

Note that $\rho_1 [1 - \alpha P_1] = \rho_2 [1 - \alpha P_2]$ by the conservation of mass, hence in the isotropic case $\rho_1 = \rho_2$. While initially the current sheet separated two magnetic regions, through reconnection, magnetic flux now crosses the boundary.

**Figure 4.1.**: Illustration of magnetic reconnection occurring at an $x$-type magnetic neutral line, where magnetic field lines (black) are antiparallel either side of a current sheet (with current $J$) where the motional electric field $E$ points out of the page. Plasma and magnetic fields flow in from the top and bottom at sub-Alfvénic speeds, and flow out toward both sides at around the Alfvén speed. Only in the diffusion region, where $R_m < 1$, is plasma not tied to magnetic field lines.

Dungey [1961] recognised that the “frozen in” condition could break down at the magnetopause, allowing reconnection between the interplanetary and terrestrial magnetic fields. Single spacecraft observations have provided in-situ evidence of the occurrence of reconnection at the magnetopause [e.g. Paschmann et al., 1979], though the large-scale spatial and temporal nature of reconnection is still not well understood. While some repeated encounters of reconnection jets at multiple magnetopause crossings have been interpreted as evidence for continuous reconnection [e.g. Sonnerup et al., 1981], there is also evidence of bursty reconnection at the magnetopause in the form of flux transfer events (FTEs). These are thought to be spatially and temporally limited reconnection events [Russell and Elphic, 1978]
which occur roughly every 8 minutes under southward IMF [Russell et al., 1996]. The magnetic field signature of a FTE is a strong core magnetic field with a bipolar variation (outward then inward or vice versa) in the component along the expected normal to the boundary, whereas plasma signatures often indicate a mixture of magnetospheric and magnetosheath plasmas [e.g. Le et al., 1999]. An example FTE event observed in the magnetosheath is shown in Figure 4.2. The magnetospheric effects of FTEs, especially their ground signatures, are still not known for sure but are thought to include ionospheric flow bursts, auroral transients, magnetic field transients and damped ULF wave packets [Glassmeier and Stel'macher, 1996].

![Figure 4.2: An example flux transfer event (FTE) observed in the magnetosheath by ISEE-2. The two solid lines enclose the whole region of the identified FTE whereas the two dashed lines enclose its central core region. From top to bottom: boundary normal components of the magnetic field; magnetic field strength; proton number density; proton flow speed; proton flow azimuthal angle; proton temperature. [From Le et al., 1999]](image-url)
4.2. Solar Wind Pressure Variations

Variations in the solar wind dynamic pressure are quite common and occur over a number of timescales [e.g. Potemra et al., 1989; Sibeck et al., 1989a]. These are associated with at least three solar wind features: shocks, holes and tangential discontinuities. Solar wind shocks, occurring every several hours to days [Burlaga and Ogilvie, 1969], have associated density and velocity increases (and occasionally decreases), thus change the solar wind dynamic pressure, typically by a factor of $\sim 3$ [Siscoe et al., 1968]. Magnetic holes, depressions in the magnetic field strength of duration $\sim 2-130$ s observed at a rate of $\sim 1.5$ per day [Turner et al., 1977], are pressure balanced structures (in the solar wind frame) [Burlaga and Lemaire, 1978] thus can contain density variations (often small enhancements) [e.g. Sibeck and Crole Jr., 1991]. Finally tangential discontinuities, which occur as frequently as every few minutes to several hours, separate plasma regions which can have different densities. Since to first order the position of the magnetopause is given by a balance of solar wind dynamic pressure to the magnetosphere’s magnetic pressure, such upstream pressure variations can perturb the boundary and have subsequent effects in the magnetosphere which are described in this section.

4.2.1. Magnetopause

Oscillatory solar wind pressure fluctuations can directly drive magnetopause motion. As the pressure increases, the boundary moves antisunward with the magnetopause current strengthening, which in turn increases the magnetic field inside the magnetosphere. Similarly, as the pressure decreases the magnetopause moves out and the current weakens, reducing the internal field. Sibeck et al. [1989b] reported a one-to-one correspondence between 8 minute period solar wind dynamic pressure variations and magnetopause motions, therefore there is observational evidence of these directly driven, quasistatic boundary motions.

A slightly different magnetopause response is expected from step-like increases in the solar wind dynamic pressure, brought by interplanetary discontinuities. Upon impacting on the magnetopause, the pressure increase compresses the boundary and launches a steep fast-mode wave in the magnetosphere which may travel faster than the convecting discontinuity. Therefore, the magnetospheric magnetic pressure increases ahead of the discontinuity and pressure balance forces the magnetopause
position outward causing a bulging ahead of the solar wind pressure front, as shown in Figure 4.3. The width of the boundary layer is also modified by this distortion as indicated in Figure 4.4.

**Figure 4.3.** An interplanetary discontinuity bringing increased solar wind dynamic pressure, launching a compressional wave within the magnetosphere. This causes magnetopause expansion ahead of the discontinuity and compression behind. [From Sibeck, 1990]

The amplitude of magnetopause motion is weakest at the point of first contact where the magnetopause simply moves radially adjusting to the change in upstream pressure [Kaufmann and Konradi, 1969], whereas further away boundary motions are greater due to the outward followed by inward motion. The plasma boundary layer also affects the size of the magnetopause motions. Since the low latitude boundary layer (LLBL) is typically thicker under Northward IMF [e.g. De Keyser et al., 2005], the compressional wave speed is reduced (the boundary layer has plasma intermediate between typical magnetosheath and magnetospheric values) hence magnetopause motions are expected to be weaker [Sibeck, 1990].

It should be noted that multipoint observations are often required when interpreting the signatures of magnetopause motion due to pressure pulses. This is because partial crossings of the boundary perturbation shown in Figure 4.4 by single spacecraft from either side can resemble the signatures of FTEs [e.g. Sibeck, 1990].

Quasi-periodic magnetopause motions \( \sim 5-20 \) min are common at the dayside magnetopause [e.g. Sonnerup and Cahill, 1967], with an example interval shown in Figure 4.5. A number of approaches have been used to model the relevant timescales of such boundary perturbations: Smit [1968] treated the nose of the magnetosphere as a rigid body, Freeman et al. [1995] considered the magnetopause analogous to
an elastic membrane, and \textit{Børve et al.} [2011] approximated the boundary as a perfectly conducting wall. All three models were linearised, resulting in damped harmonic oscillator equations of motion for the magnetopause driven by variations in the solar wind dynamic pressure. The calculated characteristic periods ranged from 2-12 min depending on solar wind conditions though were typically about 6 or 7 min, in agreement with observed magnetopause oscillations. \textit{Freeman et al.} [1995] and \textit{Børve et al.} [2011] also predicted that the magnetopause motion would be strongly damped due to the relative motion of the magnetopause and solar wind, estimating the damping ratio (the level of damping relative to the critical case) to be $\sim 0.41$. The theoretical transmissibility (ratio of output to input) of such a driven harmonic oscillator has a resonant peak of only 1.63: much lower frequencies are fully transmitted whereas higher frequency oscillations are increasingly suppressed. Therefore, the magnetopause is thought to act somewhat like a low pass filter to
4.2 Solar Wind Pressure Variations

pressure variations.

![Figure 4.5: Oscillations of the magnetopause observed by three THEMIS spacecraft with dots indicating the times and positions of observed magnetopause crossings. The magnetopause standoff distance is modelled using spline interpolation between these points, yielding oscillation half periods $T_1$, $T_2$ and $T_3$. [From Plaschke et al., 2009]](image)

4.2.2. Magnetospheric ULF Waves

Solar wind pressure variations are known to drive both direct and resonant ultra-low frequency waves in the magnetosphere. Magnetospheric ULF waves are often characterised by their frequency (rather than the physical processes which generate them) and waveform [Jacobs et al., 1964]. Quasi-sinusoidal oscillations are known as continuous pulsations (Pc), with Table 4.1 showing the classification scale in this case though the limits are not precise, whereas more irregular pulsations (Pi) are also observed.

<table>
<thead>
<tr>
<th></th>
<th>Pc1</th>
<th>Pc2</th>
<th>Pc3</th>
<th>Pc4</th>
<th>Pc5</th>
<th>Pc6</th>
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<tbody>
<tr>
<td>$T$ (s)</td>
<td>0.2-5</td>
<td>5-10</td>
<td>10-45</td>
<td>45-150</td>
<td>150-600</td>
<td>&gt;600</td>
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<tr>
<td>$f$ (mHz)</td>
<td>200-5000</td>
<td>100-200</td>
<td>22-100</td>
<td>7-22</td>
<td>2-7</td>
<td>&lt;2</td>
</tr>
</tbody>
</table>

Table 4.1.: Classification of continuous magnetospheric pulsations.

Magnetopause motion can launch compressional waves in the magnetosphere, for instance oscillatory dynamic pressure fluctuations in the solar wind drive a series of compressions in the magnetosphere of similar period [Potemra et al., 1989; Sibeck]
et al., 1989b] (see Figure 4.6 for an example). The amplitudes of these waves are greatest at their point of origin and diminish with distance. It has been known for some time that sudden changes in the solar wind pressure, as well as compressing/expanding the magnetic field all around the Earth, can trigger long period magnetospheric waves in the Pc5 band for up to about an hour [e.g. Kaufmann and Walker, 1974].

![Figure 4.6: Solar wind plasma density observed by IMP-8 (dots with dashed lines) along with simultaneous observations of the compressional component of the magnetospheric magnetic field by AMPTE CCE (solid line). The solar wind speed was steady during this interval. [From Potemra et al., 1989](image)](image)

Compressional waves in the magnetosphere can couple to local field line resonances (FLRs) [e.g. Southwood, 1974]. Since geomagnetic field lines behave like vibrating strings, due to the magnetic tension force, and their ends are (assumed) frozen in the conducting ionosphere and thus perfect reflectors, they can support quantised standing Alfvén waves known as FLRs (illustrated in Figure 4.7). There are two primary modes of FLRs in a dipole field geometry: toroidal modes with displacements $\xi$ and magnetic field perturbations in the azimuthal direction (right panels in Figure 4.7); and poloidal modes with radial displacements and magnetic field perturbations (middle panels).

The expected frequency of FLRs is often calculated using the time of flight approximation

$$f_{FLR} = \left[ 2 \int \frac{ds}{v_A} \right]^{-1}$$  \hspace{1cm} (4.3)
4.2 Solar Wind Pressure Variations

Figure 4.7: The field lines of a dipole (middle panels) may be approximated as stretched strings (left panels). The dipole lines may be displaced and oscillate in two orthogonal directions – radial (center panels) and azimuthal (right panels). The oscillation may consist of odd (top row) or even (bottom row) harmonics. The field lines are anchored at the ends (ionosphere) hence are nodes of field line displacement $\xi$, but are antinodes of the magnetic perturbation $b$. [From McPherron, 2005]

where $f_{FLR}$ is the fundamental FLR frequency, $v_A$ is the local Alfvén speed and the integration is carried out over the entire length of the field line. Whilst this makes no distinction between the poloidal and toroidal modes (they have different wave equations), their FLR frequencies are typically similar especially for the harmonics [Cummings et al., 1969]. FLR frequency estimates calculated in this way (using geomagnetic field and density models) have been shown to be in fair agreement with the full numerical treatment of the wave equations as well as with observed pulsations [e.g. Wild et al., 2005]. Since the field line length and strength as well as density in the magnetosphere vary with radial distance, the FLR frequency is L-shell dependent as demonstrated by the model profile in Figure 4.8.

Any process that displaces a field line can excite field line resonances. There is an abundance of observations showing FLRs triggered by solar wind pressure variations [e.g. Sarris et al., 2010] and these are most commonly toroidal mode. This is because azimuthal perturbations do not change the field magnitude or cause density changes
and azimuthally adjacent field lines have nearly the same resonant frequency thus can vibrate in phase. In contrast the (radially oscillating) poloidal mode is harder to excite because radially adjacent field lines have different resonant frequencies, hence field lines will inevitably oscillate out of phase and there will be compressions and rarefactions of the field [McPherron, 2005].

4.2.3. Pulsations on the Ground

The ionosphere has a variety of effects on the waves observed on the ground by magnetometers [e.g. Hughes and Southwood, 1976a, b]. These waves are in fact electromagnetic in nature, radiated from currents induced in the ionosphere, and not the incident hydromagnetic waves from the magnetosphere. In the ionosphere the electrons and ions are subject to collisions with neutrals as well as the Lorentz force, thus the conductivity is a tensor (due to the magnetic field making the medium anisotropic with regards to applied electric fields) and a generalised Ohm’s law can be written as

\[ j = \sigma_\parallel E_\parallel + \sigma_F E_\perp - \sigma_H (E \times B) / B \]  

(4.4)
where the perpendicular and parallel directions are relative to the magnetic field. The direct conductivity $\sigma_\parallel$ is the same as that in the isotropic case (the absence of a magnetic field) and depends only on the species’ collision frequencies. For perpendicular electric fields, there is an associated conductivity $\sigma_P$ in the same direction as the applied field, known as the Pedersen conductivity. Finally the Hall conductivity $\sigma_H$, due to the ions suffering more collisions than electrons, is in the $-\mathbf{E} \times \mathbf{B}$ direction which is perpendicular to both the electric and magnetic fields.

Beneath the ionosphere, the magnetic fields from incident ULF waves are cancelled by their corresponding Pedersen currents [Fukushima, 1969] (this only holds exactly for perturbations perpendicular to the ground with spatially constant conductances). Therefore, magnetic perturbations on the ground are simply due to those from ionospheric Hall currents and essentially pulsations are rotated by 90° to first order [Hughes, 1974], as illustrated in Figure 4.9.

**Figure 4.9.** Illustration of the screening effect of the ionosphere to pulsations. A wave incident on the ionosphere with magnetic perturbations $\mathbf{b}$ in the $x$ direction and electric fields $\mathbf{E}$ in the $y$ direction, where the background field $\mathbf{B}$ points downwards with respect to the ground i.e. the $z$ direction, induces horizontal currents $\mathbf{J}$ in the ionosphere (E Region) due to the Pedersen and Hall conductivities, $\sigma_P$ and $\sigma_H$ respectively. The resulting magnetic perturbations in the neutral atmosphere is in the $y$ direction, due only to the Hall currents. Therefore, incident magnetic pulsations are rotated by 90° when measured on the ground. [From Hughes and Southwood, 1976a]
4.2.4. Travelling Convection Vortices (TCVs)

The magnetopause motion and localised distortion discussed in subsection 4.2.1 results in vortical velocity and magnetic fields, which move antisunward at magnetosheath flow velocities. A pair of opposite vortices are shown in Figure 4.4(left), however in the case that the fast mode wave does not outrun the pressure front only a single vortex (the second one) would be present as no outward bulge of the magnetopause should form. These vortices have associated field-aligned currents (FACs) which map to the ionosphere as seen in Figure 4.10, carrying the information about the magnetopause motion to the ground.

FACs close in the ionosphere through Pedersen currents, completing the magnetospheric circuits, and shielding the ground from their effects. However, they do generate Hall current vortices in the ionosphere thus a pair of FACs should have an associated vortex pair in the ionosphere. Since the magnetopause distortions travel antisunward, so to do the ionospheric vortices which are known as travelling convection vortices (TCVs). Their associated ground signatures are called magnetic impulse events (MIEs) which typically show a bipolar structure in the H component (geomagnetic North-South) and a single positive or negative excursion in the D (East-West) component, making the H component variation proportional to the negative time derivative of the D component [Glassmeier et al., 1989]. In addition
networks of latitudinally separated ground magnetometers can be used to image these signatures in the ionosphere revealing the vortices (see Figure 4.11), and radars can directly measure their ionospheric convection [e.g. Engebretson et al., 2013].

Figure 4.11.: Feather plots of equivalent ionospheric currents from ground magnetometers at different geomagnetic latitudes, revealing a number of vortices (circles). [From Ridley et al., 1998]

4.3. Transient Ion Foreshock Phenomena

Transient pressure variations can also originate at the bow shock and ion foreshock, which may have magnetospheric effects. It has recently been suggested that these phenomena may be an important source of Pc5 waves in the magnetosphere [Hartinger et al., 2013].

4.3.1. Foreshock Cavities

Foreshock cavities are crater-like magnetic field dropouts filled with energetic ions [Wibberenz, 1985]. They are thought to form when the enhanced pressure of suprathermal ions within bundles of magnetic field lines connect to the quasi-parallel bow shock causing these bundles to expand outward and compress nearby plasma and magnetic fields in regions of space not connected to the bow shock [Schwartz, 2006]. Consequently, foreshock cavities can be identified on the basis of enhanced densities and magnetic field strengths bounding regions of depressed density and field strength containing a suprathermal ion component [Thomas and Brecht, 1988]. Billingham
et al. [2008] found, in a survey using Cluster data from December 2004 to May 2006, typical cavity durations to be a few minutes with interior densities and magnetic field magnitudes dropping to $\sim 60\%$ of the surrounding background solar wind. They occur preferentially in fast, moderate field strength solar wind streams and at low (high) cone angles foreshock cavities are observed outside (inside) the expected upstream boundary of the intermediate ion foreshock. The pressure changes associated with foreshock cavities can propagate through the bow shock and magnetosheath, impinging upon the magnetopause causing its motion and the compression/expansion of the magnetospheric magnetic field [Fairfield et al., 1990; Turner et al., 2011]. However, Sibeck et al. [2004] showed that multipoint observations do not always show a one-to-one correspondence between the density variations associated with foreshock cavities and the variations of the magnetic field strength observed at geostationary orbit, perhaps due to the cavities’ transverse scale size being small and thus none of the spacecraft observed the precise sequence of density variations that actually struck the subsolar magnetopause.

4.3.2. Hot Flow Anomalies (HFAs)

Hot Flow Anomalies (HFAs) are disruptions of the solar wind, lasting a few minutes, observed in the vicinity of the bow shock [e.g. Schwartz et al., 2000]. They are caused by current sheets, usually Tangential Discontinuities, interacting with the shock [Schwartz, 1995]. If the solar wind convection electric field points into the TD on at least one side, ions specularly reflected at the shock are channeled back along the current sheet [Burgess, 1989; Thomas et al., 1991] resulting in a hot ion population which expands excavating the solar wind and laterally driving pile up regions and shock waves [Fuselier et al., 1987; Lucek et al., 2004b] as shown in Figure 4.12. Schwartz et al. [2000] described a set of conditions for the formation of HFAs, which included that the discontinuity normal should make a large angle with the sunward direction such that the current sheet slowly sweeps across the bow shock allowing for the development and evolution of the non-linear structure. They also found that HFA formation was more favourable with quasi-perpendicular shock geometries on at least one side (preferentially the post HFA side) and when there was a relatively small jump in magnetic field strength associated with the discontinuity.

HFAs can generate considerable dynamic pressure fluctuations in the upstream so-
Figure 4.12.: Schematic of a hot flow anomaly (grey) forming from the interaction of a tangential discontinuity (green) with the bow shock (blue). The electric field $E$ (green arrows) pointing toward the current sheet drives particles into this layer, which expand laterally driving compressions and shocks (red). The velocity perturbations are shown as the blue lines. [From Lucek et al., 2004b]

It is clear that pressure variations originating in the pristine solar wind and those generated at the bow shock and in the ion foreshock can have effects within the magnetosphere. Often the measurements of the former are taken from far upstream of Earth at the L1 Lagrangian point and suitably time lagged, since continuous observations just upstream of the shock are not possible with the currently available spacecraft. Nonetheless it is the magnetosheath plasma that acts as the interface between these transient phenomena and the magnetopause. One in principle should be able to directly relate conditions at the magnetopause with those upstream of...
Chapter 4 Transients in the Magnetosphere

the bow shock, however this requires an understanding of how upstream phenomena are processed by the shock, evolve in the magnetosheath and impact upon the boundary. Since the solar wind - bow shock interaction is highly non-linear with many complicated feedback mechanisms, this is not simple to predict. Therefore it is important to understand the nature of transient pressure variations in the magnetosheath: their occurrence, origins and impacts upon the magnetosphere. This thesis focuses on a particular type of pressure transient, namely pulses in the magnetosheath dynamic pressure.

Observationally, a number of such pulses, sometimes described as jets or transient flux events (TFEs), have been reported in the magnetosheath and at the magnetopause (Figure 4.13 shows an interval with three example pulses). Whilst some of these can be ascribed to magnetic reconnection at either the magnetopause [e.g. Paschmann et al., 1979] or current sheets [e.g. Phan et al., 2007], many such enhancements cannot [e.g. Amata et al., 2011]. Of the latter, their kinetic energy density can far exceed that of the undisturbed solar wind and they are often found during intervals of radial IMF [Hietala et al., 2009].

The first evidence of these structures in the magnetosheath was presented by Němeček et al. [1998] who showed multi-point observations from Interball-1 and Magion-4, in the flank magnetosheath of abrupt (several tens of seconds in duration) 200-300% increases in ion flux, with flow-parallel dimensions $\sim 1 R_E$. Savin et al. [2008] reported similar structures in the magnetosheath near the southern cusp, observed by Cluster, during a constant, high speed solar wind stream. Their study found that the jets’ average duration at the spacecraft was 28 s (corresponding to $\sim 1 R_E$) and that the majority contained velocity increases relative to the ambient magnetosheath flow. In roughly 70% of the jets, peaks in the density and velocity did not coincide and the peak in the dynamic pressure more often than not corresponded to the peak in density. Further jets were shown by Amata et al. [2011] using Cluster observations near the northern cusp during quiet solar wind, who concluded that they were in general due to a combination of velocity and density enhancements but that the relative contribution of these two factors can vary considerably. Other jets qualitatively different to the above, notably due to density depressions rather than enhancements, have also been presented in the subsolar magnetosheath [Hietala et al., 2009; Shue et al., 2009].

A number of different origins have been suggested for these magnetosheath dynamic
Figure 4.13.: Cluster magnetosheath observations showing three example magnetosheath dynamic pressure pulses (marked A, B and C). From top to bottom: electron energy spectrogram; ion density (black) and kinetic energy density (red) together with the solar wind kinetic energy density (dots); GSM components of the ion velocity (x,y,z components correspond to black, red, blue); ion temperatures parallel (red) and perpendicular (black) to the magnetic field; plasma $\beta$ (red) and magnetosonic Mach number (black); GSM components of the magnetic field. [From Amata et al., 2011]
Chapter 4 Transients in the Magnetosphere

Figure 4.14: (left) Ion (a) and electron (b) energy spectrograms observed by Cluster. The ion velocity (c) is also shown together with the solar wind speed measured by ACE. The magnetopause is indicated by the dashed line. (right) Equatorial cut of the bulk plasma speed from a global MHD simulation under low Alfvén Mach number solar wind and Northward IMF. Flow speeds faster than those in the solar wind result from magnetic forces. [From Lavraud et al., 2007]

pressure pulses. Chen et al. [1993], Lavraud et al. [2007] and Lavraud and Borovsky [2008] explained observed magnetosheath speeds downstream of the Earth greater than the solar wind speed (Figure 4.14 left) as being due to magnetic forces (both the magnetic pressure gradient and the magnetic tension forces) under low Mach number solar wind and northward IMF. The observations were consistent with those predicted by global MHD model results (Figure 4.14 right). While not fundamentally transient in nature, they may appear so in time-series data due to spacecraft motion through the regions of enhanced flow speed or the motion of the magnetopause as seen in Figure 4.14 (left).

Hietala et al. [2009, 2012] proposed that ripples inherent to the quasi-parallel shock allow high flow speeds downstream, via the Rankine-Hugoniot relations. They suggested that such ripples could explain Cluster observations of fast, deflected flows close to the magnetopause under steady quasi-radial IMF, as illustrated in Figure 4.15. Such ripples could result in jets with either density enhancements or depressions, depending on whether the flow converges or diverges downstream. On the other hand, a somewhat similar explanation for fast magnetosheath flows with depressed densities was put forward by Shue et al. [2009]. Since under radial IMF the morphology of the bow shock can be concave [De Sterck et al., 1998; Cable et al., 2007], they postulated that a change back to the usual convex-shaped shock could allow a high speed solar wind flow into the normal region of magnetosheath flow.

Simulations provide a way of understanding how structures embedded within the so-
lar wind (e.g. Alfvén waves and discontinuities) could interact with the bow shock and generate magnetosheath pressure pulses. Lin et al. [1996a, b] have shown through one-dimensional MHD and both one- and two-dimensional hybrid simulations, that the interaction of interplanetary rotational discontinuities (RDs) with the bow shock can result in pressure pulses in the magnetosheath with amplitudes up to 2-3 times the background magnetosheath pressure. According to the fluid theory of shock-discontinuity interactions [Landau and Lifshitz, 1959] the original system will evolve to form a new set of MHD discontinuities as shown in Figure 4.16. The authors argue that the resulting series of discontinuities forms the dynamic pressure pulse structure in the simulations (see Figure 4.17 for an example of 1D hybrid simulation results). Across these structures the magnetic field strength decreases, the plasma density increases and the flow velocity is enhanced, resulting in an increase in the dynamic pressure. The hybrid simulations also showed that the temperature parallel to the magnetic field increases across the pressure pulses whilst the perpendicular temperature decreases, yielding a more isotropic temperature than the typical magnetosheath plasma. Tsubouchi and Matsumoto [2005] showed similar results in one-dimensional hybrid simulations, arguing that the generation and subsequent propagation of the pressure pulse structures are dominated by particle kinetics, with MHD proving an inadequate description. The two-dimensional global hybrid simulations predict the largest amplitude pulses when the local geometry of the shock changes from quasi-perpendicular to quasi-parallel or vice versa.\[Lin

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.15.png}
\caption{The effect of a bow shock ripple, with the velocity field upstream and downstream of the shock shown by the arrows. The plasma density is indicated by the shading (dark blue represents high density). If the jet is supermagnetosonic in the magnetopause frame, an additional weak shock forms. [From Hietala et al., 2012]}
\end{figure}
According to MHD theory, a rotational discontinuity RD interacting with the bow shock BS evolves the system into seven discontinuities and waves. The fast expansion wave FE’, rotational discontinuity RD1’, slow shock SS1’, contact discontinuity CD’, slow shock SS2’ and rotational discontinuity RD2’ propagate towards the magnetopause (left side) in the magnetosheath. [From Lin et al., 1996a]

Currently there is little observational evidence for dynamic pressure pulses resulting from discontinuities interacting with the shock in the ways suggested by simulations. Using the ISEE-1, -2 and -3 spacecraft, Hubert and Harvey [2000] presented two case studies (one in the flank magnetosheath and the other in the subsolar magnetosheath) demonstrating density enhancements anticorrelated with the magnetic field strength that may be consistent with these simulations. They did not discuss the magnetosheath flow velocity and hence whether or not large pressure pulses resulted. More recently Tkachenko et al. [2011] have reported THEMIS observations of dynamic changes in the magnetopause location and/or structure of magnetopause layers that were correlated with changes in the orientation of the magnetosheath magnetic field, measured further upstream. A number of these field changes exhibited density increases, but the presence or absence of magnetosheath pressure pulses was not discussed. These may also be consistent with the simulations, however in this instance the authors were unable to link the magnetosheath field changes with the IMF. Dmitriev and Suvorova [2012] presented a single magnetosheath jet event observed by THEMIS at the magnetopause with a high plasma $\beta \sim 2$ and a strong inward velocity (component normal to the boundary $v_n \sim 100$ km s$^{-1}$). The timing of the jet was in agreement with the expected arrival of an interplanetary directional discontinuity observed by ACE. This discontinuity changed the bow shock geometry from quasi-parallel to quasi-perpendicular, however the authors interpreted the jet not as the series of discontinuities resulting from the MHD theory as shown in
Figure 4.17.: One-dimensional hybrid simulation results of an RD interacting with the bow shock. RD1′ (between “a” and “b”) propagates downstream of the bow shock, as shown in the profiles and hodogram, with a field rotation angle almost the same as the initial angle. RD2′ cannot be identified in this hybrid simulation unlike MHD ones. Two slow shocks SS1′ (“b” to “c”) and SS2′ (“d” to “c”) propagate behind RD1′. The contact discontinuity cannot be identified because of the ion mixing along the magnetic field. The weak fast expansion wave cannot be clearly seen. The bow shock is located between the upstream point “f” and downstream “e”. [From Lin et al., 1996a]
Figure 4.16 but as a transient between two equilibrium states i.e. the quasi-parallel and quasi-perpendicular magnetosheaths. Since THEMIS was inside the magnetosphere either side of the jet, its properties compared to the ambient magnetosheath plasma could not be determined and compared to the predictions of simulations.

Finally, Němeček et al. [1998] postulated that the interaction of foreshock discontinuities with the bow shock could also produce similar pressure pulses to the simulations. However, they could not make a one-to-one correspondence between variations in the foreshock and the TFEs observed in the magnetosheath, explaining this due to the transverse spatial separation of the spacecraft being greater than typical foreshock correlation lengths.

4.5. Outstanding Questions

It is clear that even under fairly average solar wind conditions the magnetosheath exhibits highly complicated behaviour due to the non-linear interaction of the solar wind with the bow shock. Amongst these are abrupt enhancements in the magnetosheath dynamic pressure that could have significant impacts upon the magnetopause and within the magnetosphere. However, there are many outstanding questions regarding these structures, given the relatively few observational studies of them so far.

To date magnetosheath dynamic pressure pulses have been presented in a number of different regions of the magnetosheath under different solar wind conditions, thus how often they occur and what factors control this are poorly understood. The properties of the reported pulses show a large amount of variability, not only between different studies but also within given time intervals. Thus the typical properties of dynamic pressure pulses in the magnetosheath are by no means clear. Both of these topics could provide insight into the origins of the structures, of which a number of different mechanisms have been proposed. Many of these have little observational evidence to date, with most observational studies of dynamic pressure pulses being unable to unambiguously determine their origins. Hence it is not known whether all the proposed mechanisms occur, which physical processes dominate and under what circumstances. Finally, since these magnetosheath pulses enhance the pressure acting on the magnetopause they can potentially have impacts upon the magnetosphere. They thus provide a way of testing the understood response of
4.5 Outstanding Questions

the magnetosphere to pressure variations, but over short timescales of up to a few minutes.

Therefore, the aim of this thesis is to further the understanding of the origins, occurrence, properties and impacts of dynamic pressure pulses in the magnetosheath. Such work necessitates the use of multi-point observations and a number of different spacecraft and instrumentation have been used in the research, which are described in the next chapter.
5. Spacecraft & Instrumentation

This chapter summarises the spacecraft and ground-based assets used and their associated instruments which provide the data analysed in this thesis.

5.1. Instrument Types

5.1.1. Fluxgate Magnetometer

Fluxgate magnetometers (FGM) are instruments that measure local magnetic fields and are the most widely used sensors for space plasma applications in general and for planetary missions in particular [e.g. Balogh, 2010], since they can work over large magnetic field ranges (typically \(\sim 0.1-10,000 \text{ nT}\)) and show little drift over time. They consist of three essential parts shown in Figure 5.1: a core made from a highly magnetically permeable alloy, a driving (primary) coil and a sensing (secondary) coil. The ferromagnetic core is usually a ring around which the driving coil is wound.

Passing an alternating current through the primary coil drives the core into magnetic saturation. In the case of no background magnetic field, the two half cores (shown in blue and green in Figure 5.1) go into and out of saturation at exactly the same time, hence no voltage is induced in the secondary winding. However, if a background magnetic field with a component in the direction of the magnetisation within the core exists (as depicted by the light blue arrow in Figure 5.1) one half core will reach saturation earlier than the other during the first half of the driving cycle. This asymmetry induces a voltage in the sensing coil at two times the driving frequency, the amplitude of which is proportional to the background magnetic field. Using three cores in a triaxial setup, all three components of the background magnetic field can be measured. In spacecraft missions magnetometers are usually placed on long booms in order to reduce the effects of magnetic fields generated by the spacecraft in their measurements. However, no measurement is perfect and calibration techniques...
Figure 5.1.: Illustration of a single-axis ring core fluxgate magnetometer (FGM). This consists of a drive winding (shown in black on the left) around a core through which an alternating current is passed. This induces a magnetic field (blue and green arrows). A sense winding (shown in red on the right) around this setup is used to measure the externally applied magnetic field $H_{\text{ext}}$ via the current induced in this winding. Courtesy of Space & Atmospheric Physics, Imperial College London.

need to be used to convert the directly measured quantities by the instrument into physical values. The determination of these calibration parameters is made easier when the spacecraft spins [e.g. Kepko et al., 1996].

5.1.2. Electrostatic Analyser

An electrostatic analyser (ESA) is often used in space missions to measure the distribution function of a plasma. It employs a collimator and then an electric field to only allow charged particles with a selected energy per unit charge $E_c/q$ to be deflected into the detector [e.g. Fazakerley et al., 1995]. Therefore, such detectors cannot distinguish between particles of different masses or charge states. By stepping the plates through successive voltages a whole range of energies can be detected. Usually on a spacecraft there are two “top hat” hemispherical ESAs, one for ions and one for electrons. These are divided into a number of solid angle bins, illustrated in Figure 5.2, with the full $4\pi$ steradian angular coverage being built up as the spacecraft completes a spin about its axis. From the angular bins and different voltages one can construct the three-dimensional distribution function of the plasma from which moments can be calculated i.e. density, velocity and temperature. The capabilities of such instruments in terms of resolution and coverage are not independent and thus highly tailored to each mission.
5.1.3. Faraday Cup

A Faraday cup is a metal conductive cup designed to catch and detect charged particles. When incident ions strike the dynode surface, secondary electrons are emitted resulting in a small net charge and an induced current. The cup-like shape allows the recapture of the secondary electrons. The current flowing from the Faraday cup can thus be used to count the number of incident ions. In the case of incident electrons, the charged particles simply hit the dynode and a current is produced. Similarly to with ESAs, a voltage can be applied to the Faraday cup’s “modulator” wire-mesh grid to allow only particles of high enough energy to pass through and continue on to strike the dynode. This voltage is usually varied between two values at a frequency of a few hundred Hz, thus particles having energy between the two thresholds produce a current at the modulation frequency, as illustrated in Figure 5.3, and can easily be detected with an appropriate phase-sensitive measurement system [e.g. Ogilvie et al., 1995].

5.1.4. Electric Field Instruments

Electric field instruments (EFI) on spacecraft typically consist of spherical probes on the end of booms at 90° to one another [e.g. Pedersen et al., 1998]. The electrostatic

![Figure 5.2:](image) Schematic of a “top hat” hemispherical electrostatic analyser. The applied voltage $\Delta V$ allows only incident charged particles with energy per unit mass $E_c/q$ to be deflected through the instrument into the microchannel plate (MCP) detector. The instrument builds up a full 3-dimensional distribution of the particles by sweeping through different voltages and via the rotation of the spacecraft (white arrow). [From Bouyjou et al., 2011]
Figure 5.3.: Schematic of a Faraday cup detecting incoming ions. The velocity distribution function of ions is measured by applying a sequence of voltages (see top inset) to the "modulator" grid, which results in a current at the modulation frequency (see bottom inset) due to particles with energy between the two thresholds (particle trajectories depending on their energy are shown by the arrows). [From Ogilvie et al., 1995]

potential of the probes is measured and the electric field components are given by the difference in the measurements from opposite probes divided by the distance between them i.e. the (negative) gradient of the potential.

The potential of the spacecraft due to spacecraft charging by the photoelectric effect can also be estimated. Technically this is the electrostatic potential of the spacecraft with respect to what the potential should have been in the plasma at the spacecraft location if the spacecraft had not been there. This is a meaningful quantity as long as there are no significant electric fields in the plasma over spacecraft length scales. The spacecraft potential can in turn give a proxy of the plasma density, by assuming current balance between incoming electrons (proportional to the electron density of the surrounding plasma) and the emission of photoelectrons [e.g. Pedersen et al., 2008]. Through calibration with other instruments, continuous measurements of the density can be made via this quantity. These can be particularly useful in the cold plasmas inside the magnetosphere, which particle instruments such as ESAs are often unable to measure [e.g. McFadden et al., 2008b].
5.2. Spacecraft

5.2.1. THEMIS

The Time History of Events and Macroscale Interactions during Substorms (THEMIS) [Angelopoulos, 2008] mission is a constellation of five identical NASA spacecraft (THA, THB, THC, THD and THE), launched into orbits around the Earth in 2007. The spacecraft are spin-stabilised, with a period of approximately 3 s, and instrumentation including fluxgate magnetometers [Auster et al., 2008], electrostatic analysers [McFadden et al., 2008a] and electric field instruments [Bonnell et al., 2008]. A schematic of the spacecraft is shown in Figure 5.4.

![Figure 5.4](image)

**Figure 5.4.** Schematic of THEMIS spacecraft indicating the various instruments onboard. [From Bonnell et al., 2008]

The FGM (on the end of 2 m long booms) measures the background magnetic field
and low frequency magnetic fluctuations up to 64 Hz to a sensitivity of 0.01 nT. In this thesis, FGM data is used at either 4 vectors a second or spin resolution. The ion and electron electrostatic analysers measure plasma over the energy range from a few eV up to 30 keV for electrons and 25 keV for ions, consisting of a pair of “top hat” ESAs (iESA for ions and eESA for electrons) with common 180° by 6° fields-of-view. Only the spin resolution “reduced” ESA data is used in this thesis, which has limited solid-angle and/or energy coverage compared to “full packets” but has much higher time resolution. Finally, the EFI consists of 3 pairs of sensors on the end of wire booms. In the spin plane one pair of sensors is deployed to 20 m and the other to 25 m, whereas along the spin axis stiff telescopic booms of only 3.45 m are used. A number of different data products are produced by the EFI and in this thesis the electric field product used replaces the axial electric field estimate, which has large systematic errors, with a value computed from the spin plane field estimates and the ambient magnetic field under the assumption $E \cdot B = 0$.

Such an approximation can be used since, over the macroscopic length scales and ULF timescales of interest in this thesis, Ideal MHD is valid hence the dominant contribution to the electrodynamics arises from the perpendicular component of the electric field. It should be noted that if the magnetic field is too close to the spin plane then the error associated with this method grows. EFI data and the spacecraft potential are taken at spin resolution.

In this thesis data is used from the 2008 dayside science phase of the THEMIS mission, when the spacecraft were arrayed in approximately equatorial orbits permitting the simultaneous observations of the pristine solar wind, foreshock, magnetosheath and outer magnetosphere with apogees of 30 (THB), 20 (THC), 12 (THD & THE) and 10 (THA) $R_E$. Such a configuration is invaluable in the study of transient dayside phenomenon in the magnetospheric system.

### 5.2.2. GOES

The Geostationary Operational Environmental Satellites (GOES) are a series of spacecraft operated by NOAA in geostationary orbit above North America. They are equipped with Space Environment Monitoring Subsystems (SEMS) [Grubb, 1975] which include a magnetometer. In this thesis data from three GOES spacecraft are used: G10 (launched in 1997), G11 (launched in 2000) and G12 (launched in 2001). These three spacecraft provide, in this thesis, magnetic field measurements every
5.2 Spacecraft

512 ms at geographic longitudes of 60°W (G10), 75°W (G12) and 135°W (G11).

### 5.2.3. ACE

The Advanced Composition Explorer (ACE) is a NASA mission, launched in 1997, studying the solar wind upstream of the Earth in a Lissajous (or halo) orbit about the L1 Lagrangian point. The instrumentation aboard ACE includes a twin triaxial fluxgate magnetometer (MAG) [Smith et al., 1998], providing estimates of the IMF averaged over 16 s, and ESA instruments - the Solar Wind Electron, Proton, and Alpha Monitor (SWEPAM) [McComas et al., 1998]. The latter being a package of sensors measuring the three-dimensional distribution of solar wind beam and suprathermal electrons from about 1 to 900 eV and ions from 0.26 to 35 keV, providing moments at 64 s cadence.

### 5.2.4. WIND

The WIND spacecraft was launched in 1994 and has been located near the L1 Lagrangian point upstream of the Earth since 2004. The magnetic field instrument (MFI) [Lepping et al., 1995] on board WIND is composed of dual triaxial fluxgate magnetometers with sensor noise levels of <0.006 nT and cadences up to 44 samples per second, though in this thesis only 3 s averaged data is used. WIND has two Faraday cup ion instruments as part of its Solar Wind Experiment (SWE) [Ogilvie et al., 1995] which can produce ion distribution functions with up to 20 angular and 30 energy per charge bins every 92 seconds. Finally, the three-dimensional plasma and energetic particle investigation (3DP) [Lin et al., 1995] includes top-hat symmetrical spherical section ESAs which measure ions and electrons from ~3 eV to 30 keV, providing moments at 3 s resolution.

### 5.2.5. OMNI Database

ACE and WIND provide observations of the solar wind conditions far upstream of Earth, which can then be suitably time lagged to provide the conditions impacting upon the magnetospheric system. A number of different methods have been used to estimate the time lag required [e.g. Mailyan et al., 2008]. The simplest approach assumes a constant convective motion of solar wind disturbances along the Sun-Earth
line, however more sophisticated techniques take the positions of the monitoring spacecraft and target into account as well as the orientation of solar wind structures e.g. discontinuities.

The OMNI database combines data from multiple spacecraft (ACE, Wind, IMP 8 and Geotail) to produce an estimate of the solar wind conditions at the bow shock nose. The position of this target is given by the bow shock model of Farris and Russell [1994] ahead of the Shue et al. [1998] model magnetopause. The time lagging procedure takes into account the orientation of structures in the solar wind such that the time lag is given by

$$\Delta t = \frac{n \cdot (r_t - r_m)}{n \cdot v_{sw}}$$

(5.1)

where $r_t$ and $r_m$ are the positions of the target and monitor respectively and $n$ is the solar wind phase front normal. The normals are determined by a number of different techniques including MVA [Sonnerup and Cahill, 1967] and the cross product method [e.g. Knetter et al., 2004] amongst others. In addition to shifting data to the bow shock nose, ACE data is also shifted to the location of the WIND spacecraft to assess the predictability of solar wind variations as a function of the shift technique. Statistical studies [e.g. Case and Wild, 2012] have found overall good agreement with the lagged solar wind data from the OMNI database with in situ observations immediately upstream of bow shock. Thus the OMNI database provides generally reliable, high resolution (1 min) estimates of the solar wind conditions relevant to the magnetosphere.

### 5.3. Ground-based Instrumentation

#### 5.3.1. Ground Magnetometers

In addition to spacecraft observations, ground-based magnetometers can monitor the magnetospheric activity. Particularly useful in conjunction with the THEMIS and GOES spacecraft are the networks of magnetometers distributed across North America. These consist of a number of different arrays of magnetometer stations including THEMIS [Russell et al., 2008], Canadian Array for Realtime Investigations...
of Magnetic Activity (CARISMA), Canadian Magnetic Observatory System (CAN-MOS), Magnetometer Array for Cusp and Cleft Studies (MACCS) [Engelbrecht et al., 1995], Geophysical Institute Magnetometer Array (GIMA), Technical University of Denmark (DTU), U.S. Geological Survey (USGS), and Solar-Terrestrial Energy Program (STEP). Figure 5.5 shows a map in geomagnetic coordinates of the (abbreviated) station names and locations used in this thesis. The cadences of these magnetometers vary, being either 0.5 or 1 s.

Figure 5.5.: Map of ground magnetometer stations (black dots) in North America in geomagnetic coordinates: geomagnetic latitude $\Lambda$ along the vertical and geomagnetic longitude $\Phi$ along the horizontal, with the approximate relation between Magnetic Local Time (MLT) and Universal Time (UT) also given.

### 5.3.2. SuperDARN

The Super Dual Auroral Radar Network (SuperDARN) [Greenwald et al., 1995; Chisham et al., 2007] is an international radar network for studying the upper atmosphere and ionosphere, currently comprising twenty one radars in the northern hemisphere and eleven in the southern hemisphere. The radars transmit a short sequence of pulses in the High Frequency (HF) band, between 8.0 MHz and 22.0 MHz, and sample the returning echoes. The sequence of pulses is carefully designed to allow the Doppler characteristics of different targets to be determined at multiple ranges by using the auto-correlation function of the received samples, while the secondary antenna array provides vertical angle-of-arrival information that can be used to determine their altitude. Many sequences are transmitted and the calculated auto-correlation functions integrated over a period of several seconds to minimize
the effect of noise. The final average auto-correlation function is then used to calculate the backscattered power, spectral width and Doppler velocity of plasma density irregularities in the ionosphere.
6. Solar Wind Discontinuities Downstream of the Bow Shock


6.1. Introduction

Observations have shown that transient, large amplitude enhancements in the dynamic pressure sometimes exist in the magnetosheath (see section 4.4), however their generation is not well understood. Multi-point observations from spacecraft in the solar wind, foreshock and magnetosheath make it possible to track structures’ propagation and evolution through the system, thereby improving the comprehension of the complicated processes involved in the solar wind - bow shock interaction, which might result in such pulses. The five THEMIS spacecraft, introduced in the previous chapter, provide an invaluable resource in this respect. In this chapter, THEMIS observations of transient dynamic pressure pulses in the dayside magnetosheath are presented along with simultaneous observations of the solar wind and foreshock.

In this chapter it is shown that the spatial dimensions of the pulses are \( \sim 1 \, R_E \) parallel to the flow and \( \sim 0.2-0.5 \, R_E \) perpendicular to it, inferred from the differences in the amplitudes observed by the different spacecraft. Simultaneous observations of the solar wind and foreshock prove no similar dynamic pressure enhancements exist upstream of the bow shock and that the majority of pulses are downstream of the quasi-parallel shock. By considering previously suggested mechanisms for their generation, it is shown that these pressure pulses cannot be caused by reconnection, hot flow anomalies (HFAs) or short, large-amplitude magnetic structures (SLAMS).
and that at least some of the pressure pulses appear to be consistent with previous simulations of solar wind discontinuities interacting with the bow shock \cite{Lin et al., 1996a, b; Tsubouchi and Matsumoto, 2005}. These simulations predict large amplitude pulses when the local geometry of the shock changes from quasi-perpendicular to quasi-parallel, whilst the opposite case should also produce notable pulses but typically of lower amplitude. Therefore in a given region of the magnetosheath, some of the discontinuities in the solar wind should generate pressure pulses whereas others are expected not to.

6.2. Observations

From the dayside science phase of the THEMIS mission, 13 days were found where dynamic pressure pulses were observed in the magnetosheath and observations were also available upstream of bow shock and in the outer magnetosphere at similar local times. Out of these 13 days one, 30 September 2008, provided the best coverage of these requisite regions of the dayside magnetospheric system for several hours and is presented in detail in this chapter. The orbits in the GSE frame (see Appendix A for coordinate systems) of the THEMIS (and GOES) spacecraft are shown in Figure 6.1, with the spacecraft positions given for 15:00 UT. THB, in the solar wind, was located 18 R_E upstream of the Earth on the dawn flank. THC was initially upstream of the bow shock and encountered the shock a number of times until 19:30 UT after which it traversed the entire magnetosheath, crossing the magnetopause at 21:54 UT. THD entered the magnetosheath on its outbound pass at approximately 14:38 UT followed closely by THE at 15:01 UT. Both spacecraft remained in the magnetosheath, around 1 R_E apart, until 22:47 UT and 23:21 UT respectively. THA was also in the magnetosheath from 14:58-17:01 UT, subsequently entering the magnetosphere.

6.2.1. Magnetosheath Observations

Both THD and THE observed periods of large amplitude dynamic pressure pulses in the magnetosheath. Whilst pressure pulses can often be found on the surface of or close to the magnetopause, the focus here is purely on pressure pulses well within the magnetosheath since jets can be deflected or reflected at the boundary \cite{Amata
6.2 Observations

Figure 6.1.: Orbits of the THEMIS and GOES spacecraft projected in the x-y GSE plane for 30 September 2008 12:00-00:00 UT. The spacecraft positions are shown for 15:00 UT. The magnetopause (MP) and bow shock (BS) are shown (the solid lines) using the Farris et al. [1991] and Peredo et al. [1995] models respectively. The estimated orientation of directional discontinuities (DD) in the solar wind on this day is indicated by the dashed line with corresponding normal n.

et al., 2011] making their upstream origin more difficult to discern. An example interval of pressure pulses in the magnetosheath proper are shown in Figure 6.2. Identifying individual pressure pulses can be fairly subjective, some pulses (usually the largest in amplitude) are quite obvious however others are more subtle or vague, especially since the observed pressure profiles vary significantly between pulses. To help address this problem, only pulses with enhancements in the dynamic pressure $\gtrsim 1$ nPa are selected here. Such pressure pulses were typically of duration 10 s to 2 mins in the spacecraft frame and tended to recur on time scales of 3-5 mins, however there were also large periods of time (of the order of an hour) when no pulses were observed at all.

The amplitude of the total pressure (ion thermal + electron thermal + dynamic + magnetic) of the pulses was 1-3 times that of the ambient magnetosheath plasma (the pressure terms are described in chapter 2 and chapter 3). It is of interest to determine what the individual contributions to the total magnetosheath pressure were for these pulses. It was found that the isotropic combined ion and electron thermal pressure was fairly steady throughout the magnetosheath crossing at around 1-2 nPa, showing no large, sudden increases associated with the pulses; the magnetic
pressure was small at roughly 0.3 nPa (i.e. the plasma beta was \( \sim 5 \), but showed increases up to an order of magnitude during periods of pressure pulses); and the dynamic pressure showed abrupt enhancements around 3-10 times the average background value. It is these enhancements in dynamic pressure which caused the pulses in total pressure.

The increases in dynamic pressure were due to both enhancements in the ion density and the flow velocity. To establish which of these was dominant, and to compare with the findings of Savin et al. [2008] and Amata et al. [2011], both terms in the dynamic pressure were defined as being equal to a running average over a time scale much longer than the recurrence of pressure pulses plus some deviation i.e.
6.2 Observations

Figure 6.3.: Contributions to the dynamic pressure changes measured by THD and THE due to density (top), velocity (middle) and correlations (bottom).

\[
\rho = \langle \rho \rangle + \delta \rho \\
v^2 = \langle v^2 \rangle + \delta (v^2)
\]  

(6.1a)  
(6.1b)

where \( \rho \) is the density, \( v \) the flow velocity, angular brackets denote the time averaging procedure and \( \delta \) represents the deviation from that average. It was found that the results were not particularly sensitive to the choice of averaging period so long as it was suitably large e.g. 20 minutes as used here. Using Equation 6.1 and the approximation

\[
\langle \rho v^2 \rangle \simeq \langle \rho \rangle \langle v^2 \rangle
\]  

(6.2)

(valid given that the averaging period is much greater than the correlation scale), it is possible to consider the contribution of density and velocity enhancements to the
amplitude of the dynamic pressure:

\[
\delta P_{\text{dyn}} = \delta \left( \rho v^2 \right) = \rho v^2 - \langle \rho v^2 \rangle \simeq \rho v^2 - \langle \rho \rangle \langle v^2 \rangle \simeq \delta \rho \langle v^2 \rangle + \langle \rho \rangle \delta \left( v^2 \right) + \delta \rho \delta \left( v^2 \right) \] (6.3a), (6.3b), (6.3c), (6.3d)

The first term on the right hand side of Equation 6.3d refers to the contribution due to density increases, the second term is due to velocity increases and the third is a correlation term. These three terms are shown in Figure 6.3. It was found that the velocity increases dominated in these pressure pulses, being typically 1.5-3 nPa, whereas the contributions due to the density and correlations were roughly 0.5-1 nPa. The results of this analysis are in agreement with the more qualitative findings of Amata et al. [2011]. The direction of the flow velocity was not significantly changed during the velocity enhancements, though there were periods where nearby waves and turbulence caused some scatter in flow velocity.

During pressure pulse intervals, the probability density function (PDF) of the dy-

Figure 6.4.: Probability density functions (PDFs) of the magnetosheath dynamic pressure observed by THD during intervals without (top) and with (bottom) pressure pulses. Normal distribution fits to the data (2 standard deviations around the median) are shown in grey along with an exponential tail fit in the case of pulses (dashed line).
6.2 Observations

dynamic pressure, shown in Figure 6.4 (bottom), was fairly well described by a Gaussian distribution with an extra contribution at higher dynamic pressure forming an approximately exponentially decaying tail (similar to those shown by Savin et al. [2008]). In the absence of pressure pulses (top panel), no such tail existed. The pressure pulses were super-Alfvénic, with Alfvénic Mach numbers ($M_A$) typically 2-9, but were generally not supermagnetosonic, with only the very largest amplitude pulses (and hence fastest) having a magnetosonic Mach number ($M_{ms}$) close to unity, unlike those reported by Savin et al. [2008, 2011] which were significantly super-magnetosonic.

It can be seen in Figure 6.2 that the ion temperature, both parallel and perpendicular to the local magnetic field, shows (sometimes marginal) decreases within the pressure pulses. This is how, despite exhibiting density increases, the thermal pressure across these structures is fairly steady. The temperature decrease can perhaps be better seen in the bivariate histograms of the ion temperature against the magnetosheath dynamic pressure, as shown in Figure 6.5(left & middle). These demonstrate that for higher dynamic pressure the magnetosheath plasma was colder than average (horizontal dashed lines). The temperature decreases were greater perpendicular to the magnetic field compared to parallel and the ion temperature became approximately isotropic around the pressure pulses, as can be seen in Figure 6.2e. Indeed Figure 6.5(right) shows that no high dynamic pressure plasma was associated with highly anisotropic temperatures. These findings are consistent with those of Savin et al. [2008].

The THD and THE spacecraft were separated by roughly 1 $R_E$ throughout their

Figure 6.5.: Bivariate histograms of the ion temperature perpendicular (left) and parallel (middle) to the magnetic field and the ion temperature anisotropy (right) against the magnetosheath dynamic pressure observed by THD between 15:00-20:00 UT. Dashed lines indicate mean values over the interval.
excursion in the magnetosheath (Figure 6.1) and showed notable differences in the amplitudes of the various pressure pulses. Figure 6.6 demonstrates this disparity in amplitudes for one interval of pressure pulses, which in the most extreme cases resulted in one spacecraft observing a large enhancement in dynamic pressure with the other seeing no increase at all (e.g. at 18:51 UT). This suggests the spatial dimensions of the pulses were of the order of $\sim 0.2-0.5 \, R_E$ perpendicular to the average flow, or that pressure pulses exhibit much variability over such spatial scales. From the time differences between the observations of pressure pulses by the two spacecraft, the dimensions parallel to the flow were calculated to be $\sim 1 \, R_E$, consistent with the findings of Němeček et al. [1998] and Savin et al. [2008].

![Dynamic pressure in the magnetosheath as measured by THD and THE respectively, with pressure pulses identified by arrows. The spacecraft were separated by $\sim 0.15-0.4 \, R_E$ perpendicular to the flow at this time.](image)

**Figure 6.6.:** Dynamic pressure in the magnetosheath as measured by THD and THE respectively, with pressure pulses identified by arrows. The spacecraft were separated by $\sim 0.15-0.4 \, R_E$ perpendicular to the flow at this time.

### 6.2.2. Solar Wind Observations

During this period THB was in the solar wind and observed many discontinuities in the magnetic field. Unfortunately THB plasma data was not available so the ACE and WIND spacecraft, in the vicinity of the Sun-Earth L1 Lagrangian point, are used as upstream solar wind monitors. The orientation of discontinuity layers in the solar wind is important in being able to propagate the measured upstream solar wind at L1 to Earth [e.g. Mailyan et al., 2008]. In general this orientation
can and does vary between discontinuities, but during some intervals discontinuities are sufficiently coplanar allowing a simple constant time lag to be applied between spacecraft.

ACE magnetic field data lagged by 72 mins showed excellent agreement with THB observations between 15:00-20:00 UT (the correlation coefficient in the GSE z component was 0.95) whereas WIND data lagged by 84 mins agreed less well (especially in the GSE x and y components), since WIND was further from the Sun-Earth line. From the positions of the spacecraft and the empirical time lags between them it was found that the discontinuity layers were oblique to the solar wind flow, indeed their estimated orientation using the cross product method [e.g. Knetter et al., 2004] is shown in Figure 6.1. The magnetic field as measured by ACE is shown in Figure 6.7a, lagged here by 69 minutes to correlate to THD observations downstream of the shock (note that all discussion refers to lagged data).

ACE proton velocity data shows that this was a period of slow wind with steadily increasing velocity from \(\sim 360 \text{ km s}^{-1}\) at around 15:00 UT to \(\sim 470 \text{ km s}^{-1}\) at around 20:00 UT, with the velocity remaining approximately constant from then on. The ion density was not available for the full interval of interest, though WIND proton density and flow velocity data showed good agreement with the ACE data when available. The solar wind dynamic pressure as measured by WIND is shown in Figure 6.7g as the black line (lagged by 79 mins here to match up with THD). The solar wind dynamic pressure varied relatively smoothly and over much longer time periods than the duration of magnetosheath pressure pulses, with a standard deviation of only 0.5 nPa. The cadence of the WIND plasma instrument is not

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**Figure 6.7.** (following page): (a) Solar wind magnetic field as measured by ACE with blue, green and red representing the GSE x, y and z components respectively. ACE data has been time lagged by 69 mins to correlate with THD & THE. (b) Solar wind/foreshock magnetic field as measured by THC in GSE coordinates. Data has been lagged by 1 min and removed between 17:16-17:22 UT and post 18:32 UT for clarity as a number of shock crossings were observed. (c) \(\theta_Bn\) magnetically connected to THC. The magnetic field used is that from ACE. (d) THC ion energy spectrogram where the colour scale represents the differential energy flux in \(\text{eV/(cm}^2\text{ s sr eV)}\). (e) GSE magnetic field components as measured by THD in the magnetosheath. (f) \(\theta_Bn\) upstream of THD calculated using ACE data. (g) Upstream dynamic pressure as measured by WIND (black) in the pristine solar wind and THC (green) in the solar wind/foreshock. WIND data has been lagged by 79 mins. (h) Dynamic pressure as measured by THD and THE in the magnetosheath. Pressure pulses observed by both spacecraft are indicated by arrows. (i) Alfvénic Mach Number as measured by THD and THE.
high enough to fully resolve the pulses observed in the magnetosheath should they have existed in the solar wind. However, by averaging the THEMIS magnetosheath pressure observations to this resolution, it was found that the observed solar wind dynamic pressure variations could not account for those in the magnetosheath, hence the pulses were not present in the pristine solar wind.

6.2.3. Foreshock Observations

Upstream of the bow shock, THC observed the same discontinuities in the magnetic field as THB and ACE as well as periods of backstreaming suprathermal ions (see Figure 6.7d) and ~30-40 s ULF waves (Figure 6.7b) characteristic of the ion and ULF foreshocks [e.g. Eastwood et al., 2005]. These can be explained by the solar wind discontinuities changing the orientation of the IMF, thereby affecting the geometry of the bow shock and hence the morphology of the foreshock.

Since the system is ultimately driven by the pristine solar wind, it is desirable to be able to predict the morphology of the foreshock and existence of ULF waves using the upstream magnetic field. The presence of ULF waves in the THC data means that ACE, although further upstream, provides a better measure of the IMF, especially on this day when there is excellent overall agreement between spacecraft. By tracing the IMF as measured by ACE to a model bow shock, the magnetic field - shock normal angle $\theta_{Bn}$ at the point of intersection can be computed as a function of time. The Peredo et al. [1995] model of the bow shock was employed using general supercritical coefficients (upstream Mach numbers were $M_A \sim 8.3$ and $M_{ms} \sim 6.6$), average solar wind conditions and the shock standoff distance set by requiring the observed shock crossing of THC at 19:30 UT to lie on the model shock surface. Assuming that THC is connected to the shock by straight magnetic field lines, the orientation of each magnetic field vector can be used to identify the intersection point on the model shock and hence the angle $\theta_{Bn}$. The results of this calculation are shown in Figure 6.7c, where the acute angles have been taken. Previous studies (the statistical results of Le and Russell [1992] and those of Eastwood et al. [2005] who used a similar method to that presented here) have shown that ULF waves are observed in regions magnetically connected to the quasi-parallel shock. Figure 6.7bd shows that when $\theta_{Bn}$ dropped below $\sim 45^\circ$, THC observed suprathermal ions and ULF waves as expected.

Associated with the observed periods of ULF waves were dynamic pressure variations
in the foreshock, shown in Figure 6.7g as the green line. Since THEMIS sometimes underestimates the ion density in the solar wind [McFadden et al., 2008a, b], the electron density has been used in the calculation of the dynamic pressure measured by THC. Again the observed variations in dynamic pressure in the foreshock are dissimilar to the magnetosheath pressure pulses: they are oscillatory, rather than predominantly showing enhancements; their amplitudes (∼0.5 nPa) are much lower; and they are vastly more numerous.

6.3. Analysis

It has been shown that magnetosheath pressure pulses cannot be explained by similar pulses existing in the solar wind or foreshock, therefore they must be generated either near the bow shock or in the magnetosheath itself. Here a comparison between the observations and a number of previously proposed phenomena are made.

6.3.1. Reconnection

Simulations [e.g. Pang et al., 2010] and observations [e.g. Phan et al., 2007] have provided evidence that reconnection jets can exist in the magnetosheath due to the compression of solar wind current sheets at the bow shock. The signatures of such reconnection are accelerated plasma outflows, interpenetrating ion beams, reconnection inflows and the associated tangential reconnection electric field. While in many cases the dynamic pressure enhancements reported here seem to occur in the vicinity of changes in the orientation of the magnetosheath magnetic field, they cannot be explained by such reconnection jets: the velocity increases were much greater than the local Alfvén speed (Figure 6.7i) and there was little velocity deflection meaning the Walén relation [e.g. Walén, 1944; Gosling et al., 2005] did not hold; and no counterstreaming ion beams (which would provide evidence of magnetic connection across the exhaust [e.g. Phan et al., 2007]) were observed.

6.3.2. Hot Flow Anomalies

Savin et al. [2011, 2012] have suggested that HFAs (discussed in subsection 4.3.2) might produce fast (supermagnetosonic) streams in the magnetosheath, though
6.3 Analysis

there is little conclusive evidence of this to date. In fact previous studies of HFAs within the magnetosheath [e.g. Eastwood et al., 2008] have shown that the downstream signatures of HFAs consist of a complex series of plasma structures containing flow deflections, density cavities and hot plasma. These are all unlike the observations of pressure pulses presented here where little flow deflection is observed, the density exhibits enhancements and the plasma is colder than the ambient magnetosheath. The total pressure variations in the magnetosheath due to HFAs are also much smaller than those reported here, ~1 nPa in amplitude. In addition, upstream of the shock THC observed no HFAs and was separated from THD and THE by only ~1 RE in the GSE y-z plane. If the pressure pulses were caused by HFAs, it is expected that THC would have observed at least some of them, given the estimates of the size of HFAs ~2-3 RE [Facskó et al., 2008].

6.3.3. SLAMS/shock ripples

The dynamic pressure of SLAMS (discussed in section 3.4) can be of the order of a few times that of the solar wind. However this is due to the compression of the plasma rather than the predominantly velocity driven enhancements of the magnetosheath pressure pulses. Indeed SLAMS decrease the velocity of the solar wind plasma, thus their density and velocity are anticorrelated in the spacecraft frame unlike the magnetosheath pressure pulses, which show correlated enhancements. Therefore, the dynamic pressure enhancements of SLAMS cannot account for the pulses.

Hietala et al. [2009] proposed that local curvature changes of the quasi-parallel shock, perhaps due to SLAMS, can explain their reported supermagnetosonic jets. Their observations however are rather different to those presented here: the velocity increases exhibited significant flow deflections and at least one jet consisted of a decrease in the density sandwiched by density enhancements. Under the bow shock ripple scheme it is also not clear why many pulses occur in the vicinity of solar wind discontinuities when the IMF reported by Hietala et al. [2009] was steady and quasi-radial, which may be more conducive to the formation of SLAMS.
6.3.4. Solar wind discontinuities

The observations in the magnetosheath (Figure 6.2 & Figure 6.7) show many similarities to the hybrid simulations by Lin et al. [1996a, b] and Tsubouchi and Matsumoto [2005] based on the interaction of solar wind discontinuities with the bow shock: the dynamic pressure pulses were due to correlated density and velocity increases and the ion temperature perpendicular to the magnetic field decreased resulting in a more isotropic distribution.

If the pressure pulses were due to solar wind discontinuities, one would also expect magnetic field rotations adjacent to the pressure enhancements with an angle of rotation almost equal to that in the solar wind [Lin et al., 1996a]. Since on this day magnetic field data between spacecraft can be aligned using a simple constant time lag, ACE data (Figure 6.7a) can be compared directly with that of THD (Figure 6.7e) and THE (similar to THD). Being close to the Sun-Earth line, the shock normal upstream of THD and THE would have been principally in the GSE x direction and, according to the Rankine-Hugoniot relations, the GSE y and z components of the magnetic field downstream of the shock should have been equal to those in the solar wind multiplied by the shock compression ratio. Indeed by inspection, Figure 6.7 shows good correlation in these components between ACE and THD. It was found that the shock compression ratio was approximately 4, its typical value for high Mach number flow [e.g. Lopez et al., 2011], therefore these components of the magnetic field as measured by ACE were multiplied by this ratio and compared directly with THD and THE. The high frequency waves and turbulence in the magnetosheath data were filtered using a 16 s running average to aid the comparison. An example of such a comparison is shown in Figure 6.8, showing the general agreement between ACE and THD.

In the vicinity of pressure pulses, discontinuities in the solar wind were identified from the ACE data and similar changes in the magnetic field were sought in the magnetosheath (note the GSE x component of the solar wind magnetic field was relatively constant during the interval depicted). Two such discontinuity layers (1 & 2) as measured by ACE are indicated by the black horizontal bars in Figure 6.8 with the same discontinuities in the magnetosheath highlighted by the turquoise bars. Due to the simple constant time lag method used to match up the spacecraft data, discontinuity 1 as observed by ACE and THD are displaced from one another by about a minute, whereas for discontinuity 2 they coincide. It is clear that the
peaks in the dynamic pressure are not centred on the discontinuity layers but are adjacent to them, in agreement with the simulations. This procedure was performed for the entire dataset and many of the observed pressure pulses were found to be adjacent to large angle field rotations that were also identifiable in the solar wind. However, some pressure pulses were observed where, due to the waves and turbulence in the magnetosheath, no magnetic discontinuities could be identified despite there existing small angle discontinuities in the upstream data. This is a limitation in being able to match up the solar wind and magnetosheath magnetic fields, as for small discontinuities the inherent variability of the magnetosheath will dominate. Therefore we cannot unambiguously associate all the observed pressure pulses with solar wind discontinuities.

In the two-dimensional hybrid simulations by Lin et al. [1996b], the largest amplitude pressure pulses (2-3 times the background total pressure in amplitude) were ob-

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**Figure 6.8.:** (a) Dynamic pressure measured by THD. Pressure pulses are indicated by arrows with their approximate durations shown by the width markers. (b) & (c) GSE y and z magnetic field components as measured by ACE (black) and THD (turquoise). ACE magnetic field data has been multiplied by the bow shock compression ratio of 4 and lagged by 69 mins for comparison with THD. THD magnetic field data has been smoothed using a running average of 16 s to filter out high frequency waves and turbulence. Two discontinuities observed in both the solar wind (black horizontal bars) and the magnetosheath (turquoise horizontal bars) were found adjacent to pressure pulses. (d) $\theta_{Bn}$ upstream of THD calculated using ACE data.
served downstream of a shock which changed geometry from quasi-perpendicular to quasi-parallel due to an interplanetary rotational discontinuity. They attributed this to the large acceleration in the flow speed by the field tension force of the transmitted RD. When the shock geometry went from quasi-parallel to quasi-perpendicular they observed pressure pulses of somewhat smaller amplitude, $\sim 100\%$ the typical magnetosheath pressure. Dmitriev and Suvorova [2012] observed a magnetosheath jet consistent with this latter case.

In order to quantitatively analyse the changes in the bow shock geometry upstream of the magnetosheath spacecraft, streamlines in the magnetosheath are required to trace back the plasma parcels observed to the model shock. Since THD and THE were close to the Sun-Earth line, the simplest approximation to use is streamlines radial from the Earth. It is expected that in this region of the magnetosheath the bow shock normal upstream of the spacecraft would be relatively insensitive to the exact choice of streamline used. To test the validity of this assertion a different set of streamlines was also used from the Block-Adaptive-Tree-Solarwind-Roe-Upwind-Scheme (BATS-R-US) global MHD model [Powell et al., 1999]. This is a Physics-based code of Earth’s space environment which solves the 3D MHD equations in a finite volume, adaptive grid using numerical methods. Here the model was run using average solar wind conditions for the periods of magnetosheath pressure pulses, whereby a velocity field for the magnetosheath was obtained from which the streamlines were computed. The velocity field from the model broadly agreed with the average velocity behaviour (magnitude and direction) measured by THD and THE. The shock normals from the radial streamlines differed to those using BATS-R-US from $\sim 2^\circ$ (when the spacecraft were roughly 4 $R_E$ from the Sun-Earth line) up to $\sim 13^\circ$ (when 7 $R_E$ from the Sun-Earth line). Therefore the difference in these shock normals was typically less than the error between the Peredo et al. [1995] model and experimentally determined shock normals [Horbury et al., 2001b, 2002]. Similarly, inflating/deflating the bow shock in response to the solar wind dynamic pressure modified the bow shock normals by less than $2^\circ$, hence the model shock was kept fixed for simplicity and henceforth the BATS-R-US streamlines were used. Note that while in this region of the magnetosheath, near the nose, the use of MHD streamlines is a suitable enough approximation, given the relative insensitivity to the bow shock normal direction, in other areas this may not be the case and a more sophisticated method may be required.

Figure 6.7d shows the computed (acute) angle $\theta_{Bn}$ upstream of THD, the values for
6.3 Analysis

THE being very similar. It is clear that pressure pulses are not found in periods of quasi-perpendicular magnetosheath, explaining the long periods of time when pressure pulses were absent. Therefore, magnetosheath pressure pulses are found downstream of the quasi-parallel shock, consistent with previous results [e.g. Hietala et al., 2009].

Given that many of the pressure pulses were associated with solar wind discontinuities, it is of interest to study what the change in $\theta_{Bn}$ was due to these IMF rotations and whether these results agree with the simulations. In Figure 6.8 discontinuity 1 changed $\theta_{Bn}$ from quasi-perpendicular to quasi-parallel with a large pressure pulse following the transmitted discontinuity in the magnetosheath i.e. the quasi-parallel side. There was also a more marginal pressure pulse preceding discontinuity 2, which changed the shock geometry from quasi-parallel to quasi-perpendicular (hence on the quasi-parallel side of the discontinuity again). No other pressure pulses were observed during the period depicted in Figure 6.8, demonstrating that pressure pulses were not simply pervasive throughout periods of quasi-parallel magnetosheath on this day.

This procedure was repeated for all the observed pressure pulses, and most of the pulses that had already been associated with solar wind discontinuities were found to be similar to those in Figure 6.8 i.e. large amplitude pressure pulses seem to coincide with $\theta_{Bn}$ changes from approximately quasi-perpendicular to quasi-parallel, whilst typically smaller amplitude pulses seem to occur when $\theta_{Bn}$ changed from approximately quasi-parallel to quasi-perpendicular. This can roughly be seen in Figure 6.7f and h between 16:30-17:30 UT and 18:30-19:30 UT when there is reasonable agreement between pressure pulses and the jumps in the value of $\theta_{Bn}$. However, if one tries to predict the existence of pressure pulses from such changes in $\theta_{Bn}$ due to solar wind discontinuities, there are a number of null cases e.g. around 16:00 UT where no pressure pulse occurs. Therefore there are many instances where the observations seem consistent with the simulations of Lin et al. [1996b], but there are also a number of examples where this theory does not agree with the data. However, this may simply be due to the small spatial structure of the pulses perpendicular to the flow such that they are not seen by any given magnetosheath spacecraft.
6.4. Discussion

The origin of the transient dynamic pressure pulses presented here that is most consistent with the observations is interpreted as being through the interaction of solar wind discontinuities with the bow shock, as illustrated in Figure 6.9. A solar wind (rotational) discontinuity is convected into the bow shock. Large amplitude, transient dynamic pressure pulses are generated downstream of the shock by this interaction generally when the shock geometry changes from quasi-perpendicular to quasi-parallel or vice versa, due to the IMF rotation. No pressure pulses are found downstream of the quasi-perpendicular shock. Downstream of the quasi-parallel shock there are more dynamic pressure variations than for the quasi-perpendicular, however these variations are typically smaller in amplitude than the pressure pulses that have been associated with solar wind discontinuities. Given the estimates of the pulses’ spatial structure perpendicular to the flow of $\sim 0.2-0.5 \, R_E$, it is suggested that the pressure pulses exist in some chain-like formation adjacent to the transmitted discontinuity as shown in Figure 6.9.

These results are broadly consistent with the predictions of the simulations by Lin et al. [1996a, b] and Tsubouchi and Matsumoto [2005], however there are a number of differences. The pressure pulses observed here exhibit spatial structure perpen-
6.4 Discussion

dicular to the flow whereas those simulated by Lin et al. [1996b] appeared fairly continuous throughout the magnetosheath. It is not clear where such small scale structure would arise from the large scale sizes of interplanetary discontinuities and the extent of the quasi-parallel shock. Multi-spacecraft studies of similar pressure pulses in the magnetosheath with smaller spacecraft separations, for instance using Cluster or MMS, could provide a better understanding of the three-dimensional structure of these pulses which may assist in addressing this issue. More sophisticated global magnetospheric simulations could also provide insight. Such studies could also ratify the interpretation of the chain-like formation of pressure pulses as shown in Figure 6.9. One possible idea as to the origin of the pressure pulses’ spatial structure is due to the “patchwork” nature of the quasi-parallel bow shock, being composed of SLAMS [e.g. Lucek et al., 2004a, 2008].

In the simulations by Lin et al. [1996a, b] it was found that all solar wind discontinuities caused pressure pulses downstream of the shock, even if only small in amplitude, and that they existed throughout the magnetosheath adjacent to the transmitted discontinuity. On the other hand it has been found that only the largest of the predicted pulses from these simulations [Lin et al., 1996b] generally persist further downstream of the shock, such that the existence of pressure pulses is highly dependent on the changes to the local shock geometry. Consequently in a given region of the magnetosheath, some of the discontinuities in the solar wind will generate pressure pulses whereas others are expected not to (as illustrated in Figure 6.9). Therefore, there is a very specific subset of all solar wind discontinuities which could produce transient dynamic pressure pulses in the magnetosheath directly upstream of the Earth, which could subsequently have effects within the magnetosphere. It should be possible to predict from solar wind observations which discontinuities will result in magnetosheath pressure pulses via this mechanism. In order to do so, one must be able to prescribe the IMF immediately upstream of the bow shock. On the day presented here, the approximate coplanarity of the discontinuity layers allowed this using simple constant time lags between spacecraft. However, in general accurately lagging discontinuities to the bow shock is difficult, especially given that discontinuities that should result in pulses should have approximately radial IMF (resulting in quasi-parallel $\theta_{Bn}$) on one side and therefore the current sheets will be almost parallel to the solar wind velocity [e.g. Knetter et al., 2004] i.e. $\theta_{vn}$, the angle between the solar wind velocity and the normal to the discontinuity layer, will be close to 90°. This makes an accurate prediction of the timings of discontinuities from
upstream solar wind monitors to the bow shock difficult since the error in the time lag will be around 25 minutes [Mailyan et al., 2008]. This is an important practical limitation in the ability to predict magnetosheath pressure pulses via the interaction summarised in Figure 6.9 and highlights the need for solar wind observations within the vicinity of the shock in general.

While the magnetosheath dynamic pressure pulses reported here and by Dmitriev and Suvorova [2012] appear to be due to solar wind discontinuities, it is by no means clear whether this is true in general. A statistical study into such structures, however, could identify the typical conditions under which pulses occur and thus highlight their predominant origin. This is the subject of the next chapter.
7. Occurrence and Properties of Dynamic Pressure Pulses


7.1. Introduction

Previous studies, including that in chapter 6, into transient dynamic pressure pulses in the magnetosheath have involved case studies of only a small number of events/days at a time (as detailed in section 4.4). Whilst most studies agree that these enhancements are typically observed downstream of the quasi-parallel shock [e.g. Hietala et al., 2009, 2012], their occurrence both spatially and under different solar wind conditions is poorly understood. It is clear, simply from the observations of the different pulses in chapter 6 as well between those reported in the literature, that there is a large amount of variability to the properties of these structures. However, the typical characteristics, their range and distributions are not known. Finally a number of origins for these pulses have been suggested in the literature including magnetic slingshot effects [Chen et al., 1993; Lavraud et al., 2007; Lavraud and Borovsky, 2008], bow shock ripples [Hietala et al., 2009, 2012] and the interaction of upstream structures with the shock [e.g. Němeček et al., 1998; Savin et al., 2011, 2012] - but which physical processes dominate and under what circumstances is yet to be determined. Therefore, the first comprehensive statistical study of dynamic pressure pulses in the magnetosheath has been conducted to provide insight into these topics, which is detailed in this chapter.

It is found that large amplitude (>100%) transient enhancements of the magnetosheath dynamic pressure occur around 2% of the time, predominantly downstream.
of the quasi-parallel shock. The lack of a clear dependence on IMF clock angle and solar wind Mach number indicates it is unlikely that they can be explained by “magnetic slingshot” effects. The dynamic pressure transients (typically of duration 30 s) are most often dominated by velocity increases along with a small fractional increase in the density, though the velocity is generally only deflected by a few degrees hence does not appear consistent with the bow shock ripple mechanism. Superposed wavelet transforms of the magnetic field show that whilst most enhancements exhibit changes in the magnetosheath magnetic field, the majority are not associated with changes in the IMF. However, there is a minority of enhancements that do appear to be associated with solar wind discontinuities which cannot be explained simply by random events. In general, it is found that during periods of magnetosheath dynamic pressure enhancements the IMF is steadier than usual. This suggests that a stable foreshock and hence foreshock structures or processes may be important in the generation of the majority of magnetosheath dynamic pressure enhancements.

### 7.2. Method

#### 7.2.1. Data

This study uses Electrostatic Analyser and Fluxgate Magnetometer data from the THEMIS spacecraft during the 2008 dayside science phase of the mission. All magnetosheath crossings greater than an hour in duration from all five THEMIS spacecraft between June-September 2008 were identified manually. This was done primarily using ion energy spectrograms when available, looking for the typical shocked solar wind signature shown in Figure 7.1. Magnetosheath plasma has enhanced magnetic fields and density compared to the solar wind and decreased flow speeds which are often deflected from Sun-Earth line, thus the density, magnetic field magnitude and velocity (both magnitude and direction) were also used in identifying magnetosheath crossings and their boundaries (see Figure 7.1). The survey yielded 1,361 hours of magnetosheath data. The positions of the spacecraft during these times are shown in Figure 7.2 (left & top right) along with average magnetopause and bow shock locations.

During all the magnetosheath crossings, magnetic field measurements and ion moments were collected at 3 s resolution. The ground calibrated moments were gen-
7.2 Method

Figure 7.1.: An example crossing of the magnetosheath by THC indicated by the two magenta lines. From top to bottom: magnetic field strength, ion density, ion speed, cone angle between the ion velocity and the Sun-Earth line, and ion energy spectrogram where the colour scale shows the differential energy flux. The magnetosheath crossing was identified primarily through the latter, though the other panels are also indicators of the magnetosheath since this region contains shocked (and turbulent) solar wind plasma typically deflected from the Sun-Earth line. (c.f. Figure 3.7)

erally used, however if these were not available for a given magnetosheath crossing the on-board moments were taken instead. It was discovered that unphysical values of these on-board moments were often found adjacent to data gaps, therefore all points adjacent to data gaps were rejected. This study does not use electron plasma moments since electrons’ contribution to the dynamic pressure is negligible and their thermal pressure is generally much smaller than that of ions [e.g. Schwartz et al., 1988].

7.2.2. Magnetosheath Model

It is clear that many of the crossings lie outside the average magnetosheath due to the changing solar wind conditions, therefore data was mapped onto a stationary model of the magnetosheath. One minute resolution OMNI solar wind data (introduced in subsection 5.2.5), smoothed to 20 minutes, was used to estimate conditions upstream at the nose of the bow shock. Aberrated GSE coordinates (aGSE) were used to allow
Figure 7.2.: (top right & left) All THEMIS magnetosheath crossings greater than an hour in duration between Jun-Sep 2008 projected radially (left) and in the GSE y-z plane (top right). The average magnetopause and bow shock locations determined by the Shue et al. [1998] and Farris et al. [1991] models respectively are shown as the black lines. (bottom right) Coverage in the magnetosheath model, binned by aberrated solar zenith angle $\theta$ and fractional magnetosheath distance $F$, where the colour scale represents the amount of time in minutes spent by spacecraft in each bin. The magnetopause and bow shock are indicated by the dashed black lines.

for the Earth’s orbital motion:

\[
\hat{x}_{aGSE} = \frac{\langle \mathbf{v}_{sw} \rangle - \mathbf{v}_{E}}{|\langle \mathbf{v}_{sw} \rangle - \mathbf{v}_{E}|} \\
\hat{y}_{aGSE} = \frac{\hat{z}_{GSE} \times \hat{x}_{aGSE}}{|\hat{z}_{GSE} \times \hat{x}_{aGSE}|} \\
\hat{z}_{aGSE} = \frac{\hat{x}_{aGSE} \times \hat{y}_{aGSE}}{|\hat{x}_{aGSE} \times \hat{y}_{aGSE}|}
\]

where $\langle \mathbf{v}_{sw} \rangle$ is the smoothed OMNI solar wind vector in GSE coordinates and $\mathbf{v}_{E} = (0, -29.8, 0)$ km s$^{-1}$ is Earth’s orbital velocity. The location of the magnetopause was calculated using the model of Shue et al. [1998] whilst the bow shock standoff distance was set by Farris and Russell [1994] with the bow shock shape given by Farris et al. [1991]. Since these models are axially symmetric, the
spacecraft position in the magnetosheath model can be specified by two parameters: the aberrated solar zenith angle $\theta$ (negative for the dawn magnetosheath and positive for the dusk)

$$
\theta = \arctan \left( \frac{\sqrt{y_{aGSE}^2 + z_{aGSE}^2}}{x_{aGSE}} \right) \times \text{sign} (y_{aGSE})
$$

(7.2)

and the fractional magnetosheath distance $F$ (0 at the magnetopause and 1 at the bow shock)

$$
F (r, |\theta|) = \frac{r - r_{mp} (|\theta|)}{r_{bs} (|\theta|) - r_{mp} (|\theta|)}
$$

(7.3)

where $r$ is the radial distance of the spacecraft from the Earth and the radial distances to the model magnetopause and bow shock as a function of $|\theta|$ are $r_{mp} (|\theta|)$ and $r_{bs} (|\theta|)$.

Of the 1,361 hours worth of magnetosheath data, 1,260 hours had available OMNI data and these were mapped to the magnetosheath model. The coverage in this model is displayed in Figure 7.2 (bottom), showing good coverage of the whole dayside magnetosheath and fairly good agreement with the model magnetopause and bow shock positions, with 1,167 hours for which $0 < F \leq 1$. The spatial parameterisation (in $\theta$ and $F$ coordinates) of the magnetosheath model was checked by comparing the ratio of observed to upstream conditions with those predicted by the BATS-R-US global MHD model [Powell et al., 1999] under typical solar wind conditions (Parker spiral IMF, solar wind speed 400 km s$^{-1}$ and number density 5 cm$^{-3}$). These comparisons are shown in Figure 7.3d-h, where the colours relate to the observations and the black contours are the MHD predictions. Overall there was very good qualitative agreement of the quantities mapped to the magnetosheath model. The same conclusions were made in statistical BATS-R-US comparisons to observations using Interball [Šafránková et al., 2004] and Cluster [Daum et al., 2008], thus the parameterisation of the position in the magnetosheath is likely reliable.
Figure 7.3.: (a) Number density from BATS-R-US with streamlines (black) in the aGSE x-y plane. The Shue et al. [1998] magnetopause and Farris et al. [1991] bow shock models are indicated by the white lines. Streamlines from the semi-empirical model of Kallio and Koskinen [2000] are also shown (magenta). (b) Angular difference in bow shock normals determined from MHD and semi-empirical model streamlines. (c) Angular difference in magnetosheath velocity between semi-empirical model and observations. (d-f) Ratios of the magnetosheath and solar wind number densities (d), speeds (e) and magnetic field strengths (f). (g-i) Ratios of the magnetosheath dynamic (g), thermal (h) and magnetic (i) pressures to the solar wind pressure. The black contours in (d-h) represent the same quantities from BATS-R-US.

7.2.3. Estimating $\theta_{Bn}$

As was found in chapter 6, the geometry of the bow shock is important with regard to magnetosheath dynamic pressure pulses, therefore estimates of the magnetic field - shock normal angle $\theta_{Bn}$ are required. Since the direction of the IMF often varies
7.2 Method

over minute time scales [e.g. Vasquez et al., 2007], using 1 minute resolution OMNI data of the IMF at the bow shock nose is insufficient hence a better estimate of the IMF associated with each magnetosheath plasma parcel is required.

In this study an automated clock angle (in the $B_y$-$B_z$ plane perpendicular to the Sun-Earth line) correlation procedure was used to match up the magnetic fields observed by ACE [Smith et al., 1998] at 16 s cadence to those in the magnetosheath, the details of which can be found in Appendix C. This technique resulted in estimates of the IMF 70% of the time.

Estimates of the shock normal are also needed. The semi-empirical magnetosheath model of Kallio and Koskinen [2000] was used to trace streamlines back to the model shock, since it is computationally inexpensive and provides streamlines consistent with the magnetopause and bow shock models used (the forms of these boundaries are an input to the model). This provides a shock normal at all times the spacecraft were in the model magnetosheath i.e. $0 < F \leq 1$. To establish the sensitivity of the shock normals to the choice of streamlines, a comparison was made with those from BATS-R-US. Figure 7.3a shows these in black and the Kallio and Koskinen [2000] ones in magenta. Whilst the streamlines are quite different, the angular difference in the shock normals at each position (Figure 7.3b) was generally small, of the order of a few degrees, for the majority of the magnetosheath surveyed in this study. The normals are least sensitive to the streamline choice close to the shock and in the subsolar magnetosheath, whereas the largest differences of $\sim 15^\circ$ arise in the far flanks when close to the magnetopause (which has comparatively little coverage in the survey). The Kallio and Koskinen [2000] streamlines were also validated against the observations, with the average angular differences as a function of position shown in Figure 7.3c. The velocities agree well in the flanks, where the shock normals are most sensitive to differences in the streamlines, whereas in the (less sensitive) subsolar magnetosheath the deviation is typically around $15^\circ$ with the largest differences near the magnetopause. Thus overall the resulting shock normals are generally reliable and can be combined with the lagged ACE data to give estimates of the magnetosheath $\theta_{Bn}$.

7.2.4. Dynamic Pressure Pulses

In order to identify dynamic pressure pulses in the magnetosheath, an ambient dynamic pressure must first be defined. This was set equal to a 20 minute running
average of the magnetosheath dynamic pressure, a time scale much longer than
the typical recurrence of dynamic pressure pulses of a few minutes (as noted in
chapter 6). The fractional change in the dynamic pressure was then calculated and
a threshold implemented with pulses defined as

$$\frac{\delta P_{\text{dyn}}}{\langle P_{\text{dyn}} \rangle} > 1 \quad (7.4)$$

where $P_{\text{dyn}}$ is the observed magnetosheath dynamic pressure, angular brackets de-
note the time averaging procedure and $\delta$ represents the deviation from that average.
No such pulses were present in the 1 minute OMNI data or 3 s ion data from WIND’s
3-D Plasma and Energetic Particle Investigation [Lin et al., 1995]. Therefore no
identified magnetosheath dynamic pressure pulses are due to such large amplitude
pulses existing in the solar wind.

### 7.3. Occurrence

Overall dynamic pressure pulses constituted $\sim 2\%$ of the entire magnetosheath data
set. In order to understand their occurrence, the magnetosheath data was binned by
a number of different variables and the fraction of data points satisfying Equation 7.4
in each bin calculated. Any bin with less than 10 minutes’ worth of coverage was
rejected. In order to reduce noise, a nearest neighbour smoothing procedure was
implemented. Figure 7.4 shows the results of this analysis.

The occurrence of pulses has a strong dependence on $\theta_{Bn}$, being more frequent ($\sim 3\%$
of the time) when downstream of the quasi-parallel shock compared to the highly
perpendicular case ($\sim 0.5\%$), consistent with Němeček et al. [2001], Hietala et al.
[2009, 2012] and the results of chapter 6. The top panel in Figure 7.4 also shows the
variation with aberrated solar zenith angle $\theta$. As no strong dawn-dusk asymmetry
in the occurrence of pulses was observed, the absolute value is used. It is clear that
dynamic pressure pulses are more frequent behind the quasi-parallel shock for all
zenith angles. Pulses also become more common as $|\theta|$ decreases; this is the case
irrespective of geometry but is more distinct behind the quasi-perpendicular shock.
However, this behaviour may be an effect of the ambient plasma velocity, which is
7.3 Occurrence

Figure 7.4: Filled contour plots where the logarithmic colour scale represents the fraction of the time that dynamic pressure pulses ($\delta P_{\text{dyn}}/\langle P_{\text{dyn}} \rangle > 1$) are observed. All panels show the absolute cosine of the magnetic field - shock normal angle $|\cos \theta_{BN}|$ along the vertical. Across the horizontal are (top) the aberrated solar zenith angle $|\theta|$, (bottom left) magnetosheath fractional distance $F$ shown for the subsolar ($|\theta| < 30^\circ$) case, and (bottom right) solar wind speed for the subsolar inner ($|\theta| < 30^\circ$ and $F < 0.5$) magnetosheath. White areas indicate poor coverage from the magnetosheath survey.

faster in the flanks than the subsolar magnetosheath, since a larger velocity increase would be required to produce a given fractional change $\delta P_{\text{dyn}}/\langle P_{\text{dyn}} \rangle$.

The pulse occurrence as a function of fractional magnetosheath distance $F$ for the subsolar ($|\theta| < 30^\circ$) magnetosheath is shown in Figure 7.4 (bottom left). This reveals that the origin of the pulses behind the quasi-parallel and quasi-perpendicular bow shocks appear to be different. Pulses downstream of the quasi-parallel shock appear to be generated at the shock itself, since there is no obvious trend in their occurrence with $F$. This is also the case in the flanks (not shown). In contrast the frequency of pulses increases near to the magnetopause behind the quasi-perpendicular shock (though the trend is weaker in the case of the flanks). This could imply that they are associated with the magnetopause.

Finally, the variation with solar wind speed for the subsolar inner magnetosheath ($|\theta| < 30^\circ$ and $F < 0.5$) is shown in Figure 7.4 (bottom right) with an increase in the occurrence of pulses with solar wind speed seen, especially behind the quasi-perpendicular shock. No such relationship could be determined for the outer subsolar or either flank cases since data coverage was insufficient to select by $F$. Note that
in the inner, quasi-perpendicular magnetosheath, identified pulses may be due to reconnection at the magnetopause or acceleration near the plasma depletion layer, hence the reason behind the trend with solar wind speed is unclear.

Similar analysis (not shown here) demonstrated that the occurrence of dynamic pressure pulses in the magnetosheath showed no clear dependence on the IMF clock angle, solar wind plasma $\beta$ or Mach number. Therefore it is unlikely that the pulses can be explained by the “magnetic slingshot” effects described by Chen et al. [1993], Lavraud et al. [2007] and Lavraud and Borovsky [2008], which come into play predominantly downstream of the Earth (this study looks into the dayside only) under low Mach number solar wind and northward IMF. Using 200% pulses rather than 100% does not make a qualitative difference to the results presented here. These are in agreement with the statistical study of magnetosheath ion flux variations by Němeček et al. [2001], which showed an increase in the relative standard deviation toward the magnetopause, as the IMF cone angle decreased and solar wind velocity increased respectively. However, it has been shown here that the behaviour with position in the magnetosheath and the solar wind speed is very different depending on the magnetosheath $\theta_{Bn}$, hence this is the main controlling parameter in the occurrence of dynamic pressure pulses.

## 7.4. Properties

Dynamic pressure pulses of up to $\sim$15 times the background in amplitude were observed by THEMIS. The dynamic pressure can vary due to either density or velocity variations or both. This section addresses which of these is dominant.

### 7.4.1. Parameter Space

The same technique as in subsection 6.2.1 was employed, whereby both terms in the dynamic pressure are expressed as being equal to a background value (given by a 20 minute running average) plus some deviation (Equation 6.1) and the approximation of Equation 6.2 was found to be within 10% for 99% of the magnetosheath survey. Equation 6.3d can be manipulated to consider the relative contributions of
fractional density and velocity variations to the changes in the dynamic pressure:

\[
\delta P_{\text{dyn}} \simeq \frac{\delta \rho}{\langle \rho \rangle} \langle \rho \rangle \delta \left( \frac{v^2}{\langle v^2 \rangle} \right) + \delta \rho \frac{\delta}{\langle \rho \rangle} \frac{\delta (v^2)}{\langle v^2 \rangle} \quad (7.5a)
\]

\[
1 \simeq \frac{\delta P_{\text{dyn}} / \langle P_{\text{dyn}} \rangle}{\delta P_{\text{dyn}} / \langle P_{\text{dyn}} \rangle} + \frac{\delta P_{\text{dyn}} / \langle P_{\text{dyn}} \rangle}{\delta P_{\text{dyn}} / \langle P_{\text{dyn}} \rangle} \quad (7.5b)
\]

\[
\simeq \frac{\delta \rho / \langle \rho \rangle}{\delta P_{\text{dyn}} / \langle P_{\text{dyn}} \rangle} + \frac{\delta (v^2) / \langle v^2 \rangle}{\delta P_{\text{dyn}} / \langle P_{\text{dyn}} \rangle} + \frac{(\delta \rho / \langle \rho \rangle) (\delta (v^2) / \langle v^2 \rangle)}{\delta P_{\text{dyn}} / \langle P_{\text{dyn}} \rangle} \quad (7.5c)
\]

As in subsection 6.2.1, the first term on the right hand side of Equation 7.5c (here referred to as the density term) refers to the contribution to the dynamic pressure due to density variations, the second term is due to velocity changes (velocity term) and the third (correlation term) relates to changes in both.

The relative contributions of density and velocity variations to the dynamic pressure transients can then be represented in the density-velocity term parameter space. Since its construction makes no assumption as to the sign or magnitude of the change in dynamic pressure it is completely general. In this study, however, only data satisfying Equation 7.4 is used hence only a subset of the full parameter space is investigated.

### 7.4.2. Distribution

Figure 7.5a shows the distribution of pulses in the density-velocity term parameter space. The pulse amplitude \( \delta P_{\text{dyn}} / \langle P_{\text{dyn}} \rangle \) is a function of the position in this parameter space.

**Figure 7.5. (following page):** (a) Distribution of dynamic pressure pulses in the density-velocity term parameter space where the colour scale is the number of data points in each bin. The black dot marks the maximum of the distribution. Three different regions are indicated by the magenta lines. Contours of \( \delta P_{\text{dyn}} / \langle P_{\text{dyn}} \rangle \) are given by the black dashed lines, where the black arrows specifying the direction of increasing \( \delta P_{\text{dyn}} / \langle P_{\text{dyn}} \rangle \) in the different regions. (b-m) Means in each parameter space bin of the (b) aberrated solar zenith angle; (c) fractional magnetopause distance; (d) fractional temperature change; (e) fractional magnetic field strength change; (f) fractional ion thermal pressure change; (g) fractional change in ion thermal and magnetic pressures; (h) fractional total pressure change; (i) fractional radially inward pressure change; (j) change in the velocity cone angle; (k) Alfvénic Mach number; and magnetosonic mach numbers for both the (l) subsolar and (m) flank cases.
Chapter 7
Occurrence and Properties of Dynamic Pressure Pulses

\[
\frac{\delta \rho}{\langle \rho \rangle} / \frac{\delta P_{\text{dyn}}}{\langle P_{\text{dyn}} \rangle}
\]

\[
\frac{\delta v^2}{\langle v^2 \rangle} / \frac{\delta P_{\text{dyn}}}{\langle P_{\text{dyn}} \rangle}
\]

Density Decreases
Velocity Decreases
Density Increases
Purely velocity driven enhancements
Purely density driven enhancements

\[
\frac{\delta P_{\text{dyn}}}{\langle P_{\text{dyn}} \rangle}
\]

\[
\frac{\theta_{v\times} - \theta_{v\times}}{\langle v\times \rangle}
\]

\[
M_A
\]

\[
M_{ms} (|\theta| < 30^\circ)^1
\]

\[
M_{ms} (|\theta| \geq 30^\circ)^1
\]

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7.4 Properties

eter space, contours of which are shown as the black dashed lines. The distribution is fairly continuous, however it is possible to divide it up into three main regions:

1. **Density decreases**: 18% of pulses show a decrease in density but increase in velocity.

2. **Density increases**: 82% contain increases in both density and velocity. The largest amplitude pulses are in this category.

3. **Velocity decreases**: Pulses where the velocity decreases (by a few percent) but the density increases (at least doubles) are extremely rare. These could be related to the “embedded plasmoids” of Karlsson et al. [2012], however no further discussion shall be made here.

Figure 7.5a shows that the dynamic pressure increase of the transients is typically dominated by the velocity, with the peak in the distribution (shown by the black dot) being close to a density term of zero. This is likely because the velocity in the dynamic pressure is squared: for a given fractional increase in velocity, the fractional increase in the velocity squared will be greater. Indeed modelling the fluctuations $\frac{\delta v}{\langle v \rangle}$ and $\frac{\delta \rho}{\langle \rho \rangle}$ as normally distributed random variables (with zero mean and a number of different standard deviations) yields fairly similar parameter space distributions and roughly the same partition between density increase and decrease events. However, it is of course important to understand the physical processes which generate such large fluctuations in these properties.

7.4.3. Typical Properties

In order to ascertain for the first time the typical properties of the pulses, the means of various quantities in each parameter space bin were calculated. These results are shown in Figure 7.5b-m, where bins with fewer than 4 data points have been neglected.

7.4.3.1. Density Decreases: Flux Transfer Events

Pulses with density decreases seem to generally be observed at small $\theta$ and $F$ (panels b-c), therefore could be associated with the subsolar magnetopause. Flux Transfer Events (FTEs), introduced in section 4.1 and thought to be spatially and temporally limited reconnection events occurring at the dayside magnetopause [Russell and
Elphic, 1978], are thus a likely candidate. The signatures of FTEs observed in the magnetosheath include a decrease in the density, increase in temperature, increase in the magnetic field strength and sometimes an enhancement of flow speed [e.g. Le et al., 1999]. Indeed Figure 7.5d-e demonstrates that the density decreases exhibit all of these properties. Furthermore the velocity, whilst enhanced, is around the local Alfvén speed (panel k) and highly deflected but generally to increasing cone angle (panel j), which again are consistent with a FTE origin.

FTEs would be expected at the subsolar magnetopause under southward IMF. To test this, the mean IMF clock angle $\alpha$ and acute cone angle $\theta_{Bx}$ were calculated in the parameter space bins from the lagged ACE data. Figure 7.6 shows these results, demonstrating that the density decreases typically occur under southward and high cone angle IMF. In contrast, the density increases are generally observed at smaller cone angles i.e. behind the quasi-parallel shock. Therefore apart from the bipolar magnetic field signature, which cannot be extracted from this analysis, the average behaviour of the density decreases has been shown to be consistent with FTEs.

$$\frac{\delta P_{\text{dyn}}}{<P_{\text{dyn}}>}$$

Figure 7.6.: Variation of the IMF clock angle $\alpha$ (left) and acute cone angle $\theta_{Bx}$ (right), for dynamic pressure pulses, in the same format as Figure 7.5.

### 7.4.3.2. Density Increases

It has been established that pulses with density increases tend to occur downstream of the quasi-parallel shock, but their typical properties are still unclear. Figure 7.5b shows that the more density driven pulses tend to occur in the flanks. This seems consistent with previous case studies where subsolar pulses have been reported as being generally dominated by velocity enhancements, as noted in chapter 6, whereas
those in the flank show relatively more density driven enhancements [Savin et al., 2008; Amata et al., 2011]. The latter of these could be density pileups as previously reported by Savin et al. [2008]. These might be expected more often in the flanks as the streamlines followed back to the shock are longer than in the subsolar case, meaning more ambient plasma could be compressed by a velocity enhancement that originated at the shock.

Previous studies [Hietala et al., 2009, 2012; Savin et al., 2011, 2012] have focussed on whether the velocity becomes supramagnetosonic in these transient structures. Figure 7.5k-m show the Alfvénic and magnetosonic Mach numbers. The density increases are generally highly super-Alfvénic throughout the magnetosheath, hence cannot be explained by reconnection since the Walén relation [e.g. Walén, 1944; Gosling et al., 2005] is not obeyed. The magnetosonic Mach number shows different behaviours in the subsolar ($|\theta| < 30^\circ$) and flank ($|\theta| \geq 30^\circ$) regions. In the latter, since the ambient flow is faster, typically all dynamic pressure pulses are supramagnetosonic, whereas in the subsolar magnetosheath only pulses with amplitudes $\delta P_{dy} / \langle P_{dy} \rangle \gtrsim 4$ typically are. Therefore, the pulses’ magnetosonic Mach number is highly dependent on the position in the magnetosheath, thus this quantity may not be particularly helpful in identifying these structures.

The velocity is typically deflected to decreasing cone angle $\theta_{\alpha x}$ (panel j) i.e. towards the Sun-Earth line, consistent with the solar wind flow not being fully shocked e.g. via bow shock ripples [Hietala et al., 2009, 2012]. However, the size of this deflection is much smaller than would be expected from these theories at typically only a few degrees.

The density increases are colder than their surroundings (Figure 7.5d), consistent with the results of Savin et al. [2008] and the observations in chapter 6, though the ion thermal pressure $P_{th} = nk_BT$ shows a small increase (panel f); overall the density variations dominate the thermal pressure in these structures. The majority of the density increases have a very small decrease in the magnetic field strength (panel e). Magnetic depressions are expected from simulations of rotational discontinuities interacting with the bow shock [Lin et al., 1996a, b; Tsubouchi and Matsumoto, 2005], though the observed depression here is much weaker than in the simulations.

There is a transition in the magnetic field behaviour whereby the field strength increases for pulses with $\delta \rho / \langle \rho \rangle \gtrsim 0.4$. Whilst it is not clear what causes this, it may be an effect of simple compression of the plasma. The magnetic field increases affect
the thermal plus magnetic pressure \( P_{th+B} = P_{th} + P_B \), deviating from approximate pressure balance (panel g).

The dynamic pressure pulses significantly increase the total (dynamic + ion thermal + magnetic) pressure, up to \( \sim 2 \) times the ambient (panel h). In terms of the potential magnetospheric impact, the change in the radially inwards pressure was calculated (panel i)

\[
P_r = \rho v_r^2 \times \text{sign} (v_r) + P_{th} + P_B
\]  

(7.6)

where \( v_r = -\mathbf{v} \cdot \mathbf{r}/r \) is the component of the ion velocity directed radially towards the Earth. For \( \delta P_{dyn}/\langle P_{dyn} \rangle \gtrsim 2 \) this shows increases of \( \sim 50\% \), which could have significant effects on the magnetopause and within the magnetosphere. These pulses occur in the magnetosheath \( \sim 0.3\% \) of the time.

The typical properties of magnetosheath pressure pulses have, for the first time, been identified in this section. These have ruled out reconnection as their main cause, however, cannot unambiguously identify the predominant origin of the pulses from those previously proposed.

### 7.5. Superposed Epoch Analysis

To aid the identification of the dominant mechanism responsible for generating dynamic pressure pulses, a superposed epoch analysis (SEA) was performed on all events.

#### 7.5.1. Event Identification

Individual dynamic pressure enhancements were identified as local maxima greater than unity, separated by at least a minute (the largest peak is chosen if more than one exists within this timespan) in the 5 data point (15 s) smoothed time series \( \delta P_{dyn}/\langle P_{dyn} \rangle \) of each magnetosheath crossing. From here on in, the amplitude refers to the height of the peak in this smoothed time series and the zero epoch is set as the time of this peak. 2,617 enhancements were identified using this procedure, with the distribution of the pulse amplitudes shown in Figure 7.7 (top) as the
black histogram. The (Kaplan-Meier estimate of the) complementary cumulative distribution function (CCDF), or tail distribution, of the enhancement amplitudes is also shown (along with the 95% confidence bounds calculated using Greenwood’s formula [Cox and Oates, 1984]), revealing that \( \sim 25\% \) of the pulses had amplitudes greater than 2.

![Figure 7.7:](image)

**Figure 7.7:** (top) The distribution (black) and tail distribution (blue) of the dynamic pressure pulse amplitude. The 95% confidence interval of the latter is shown as the shaded area. (bottom) Distribution of enhancements’ full width at half maximum (FWHM) in seconds as measured in the spacecraft frame.

The duration in the spacecraft frame of the individual enhancements was also estimated from the smoothed time series. Either side of the peak, the first three successive data points that were all less than half the amplitude were identified. The time difference between the nearest of these sets of data points to the peak was used as an estimate of the full width at half maximum (FWHM). Figure 7.7 (bottom) shows the distribution of the FWHM, which ranged between 12-201 s with a mean of 34 s and standard deviation of 32 s. These results are consistent with previous estimates of enhancements’ durations [Němeček et al., 1998; Savin et al., 2008].
7.5.2. Results

Results from the SEA are shown in Figure 7.8 where the mean is shown; the median yielded qualitatively similar results. While this procedure averages over all pulses of all types, it is dominated by the more common velocity driven, density increase events.

![Figure 7.8.](image)

**Figure 7.8.:** Superposed epoch analysis of dynamic pressure pulses. (a) Fractional change in dynamic pressure, (b) Fractional change in density, (c) Fractional change in flow speed, (d) Angular deflection of the velocity, (e) Temperature anisotropy (ratio of perpendicular and parallel temperatures). Solid black lines represent the mean values and corresponding standard deviations and 95% confidence intervals are shown in grey and blue respectively (the latter being very small in the top 3 panels).

The SEA produced a dynamic pressure pulse whose position in the density-velocity term parameter space is not dissimilar to the peak of the distribution (the black dot in Figure 7.5a). While the standard deviations are large (as expected given the distribution) they are fairly constant in epoch time, thus due to the large number of events the confidence interval in the mean is small. The results of the SEA for
7.5 Superposed Epoch Analysis

other quantities were found to be in agreement with the typical properties identified in section 7.4.

In addition the analysis produced results on the total angular deflection of the velocity increases inside the dynamic pressure transients. SEA of the angle between the observed and smoothed velocity vectors is shown in Figure 7.8d. This is necessarily a positive quantity and therefore does not average to zero outside of the dynamic pressure transient. Indeed the ambient value, which signifies the typical background variability of the velocity direction, is rather large at around 20°. This is likely due to events being more common in the quasi-parallel magnetosheath, which is generally more turbulent [e.g. Lucek et al., 2005]. The deflection angle inside the dynamic pressure transient is only a few degrees larger than this ambient value, therefore the change in direction of the velocity of the pulses is not much more than the natural variability. Again the standard deviation, whilst large, is similar both inside and outside of the transient.

Hietala et al. [2009, 2012] proposed that dynamic pressure pulses could be explained by ripples in the bow shock allowing fast streams of plasma downstream via the Rankine-Hugoniot relations, necessarily deflecting the plasma flow significantly. Since SEA shows that the flow is greatly enhanced but not highly deflected compared to the ambient plasma (which has no such enhancement in the flow), it is unlikely that these ideas can explain the typical behaviour of magnetosheath dynamic pressure pulses. Nonetheless, the analysis does not preclude that some pulses may originate from such ripples.

The temperature anisotropy \( T_\perp/T_\parallel \) is displayed in Figure 7.8e, demonstrating a decrease in the vicinity of the dynamic pressure pulse. Such decreases in the temperature anisotropy have previously been observed in dynamic pressure enhancements [Savin et al., 2008; Amata et al., 2011]. However, this decrease is not confined simply to the enhancement itself, with the anisotropy only gradually increasing as one moves away from zero epoch time, consistent with the observations in chapter 6. The asymptotic value of the anisotropy is also lower than typical value for the entire magnetosheath survey of 1.4. These results suggest that the decrease in anisotropy is not necessarily associated with the just the dynamic pressure pulses but could be due to the events tending to occur in the quasi-parallel magnetosheath, which generally has a more isotropic temperature due to the less sharp shock transition compared to the quasi-perpendicular case [Génot et al., 2009].
7.5.3. Association with discontinuities?

A number of proposed mechanisms for the generation of magnetosheath dynamic pressure pulses require a solar wind discontinuity interacting with the bow shock in some way [e.g. Lin et al., 1996a, b; Savin et al., 2011, 2012]. Are pulses typically associated with discontinuities?

Identifying discontinuities is often difficult, especially in the magnetosheath, and a number of different selection criteria with different thresholds have previously been developed [e.g. Smith, 1973; Vasquez et al., 2007]. These methods attempt to identify the magnetic fields either side of the discontinuity. Since the proposed mechanisms for the pulses generally have no preferred magnetic orientation other than one side being quasi-parallel, SEA of the individual components of the magnetic field would not be expected to produce a signal. However, if one is simply interested in whether the magnetic field changes at all, then the wavelet transform can provide insight (a brief introduction to wavelet analysis can be found in Appendix D). The wavelet transform of a discontinuity (or jump) in a time series is seen as an increase in power at all frequencies, limited in time by the wavelet’s cone of influence centred on the discontinuity.

The Morlet wavelet transform of the three GSE magnetic field components were calculated, as per Torrence and Compo [1998], for both the THEMIS and ACE data. In order to exclude any edge effects from the analysis, only events with a full (i.e. no data gaps) 10 minutes’ worth of magnetic field data either side were used, resulting in 1,707 pulses from THEMIS and 1,187 from ACE. Superposed epoch analysis was performed on the wavelet power $P$ for each component of the magnetic field as well as the total power in all components, shown in Figure 7.9 where the background (at $\pm 4$ min epoch time) power law spectrum $P_{pow}$ has been subtracted for clarity. The results of the analysis were unaffected by only selecting those events with both THEMIS and ACE wavelet transforms.

In the magnetosheath the wavelet power in all three components shows a significant increase at all frequencies around the events, though this is smallest in the x component. The increases are fairly well described temporally by the Morlet wavelet’s cone of influence centred on the feature (shown by the white lines in Figure 7.9), suggesting a sharp change in the field. The same feature is observed when the median is used in the analysis, hence these results are not simply due to highly skewed distributions. A null analysis was also performed, using the same number of events.
Figure 7.9.: (left) Mean of the superposed wavelet power of the magnetosheath magnetic field. The median was similar. (middle & right) Mean (middle) and median (right) of the superposed wavelet power of the solar wind magnetic field. The four panels show the power in the three GSE components of the magnetic field as well as the total. The respective mean background power law spectra $P_{\text{pow}}$ over all three components have been removed for clarity, with a similar procedure performed for the total power also. White lines indicate the Morlet wavelet cones of influence.

but picked entirely at random, which yielded no features. Figure 7.10 shows that the background total wavelet power is larger for the dynamic pressure pulses than would be expected by chance: this is probably because events tend to occur in the quasi-parallel magnetosheath, which contains larger fluctuations in the magnetic field [Luhmann et al., 1986]. It has been found here that dynamic pressure pulses typically have associated sharp changes in the magnetosheath magnetic field which may be discontinuities.

To ascertain whether these changes in the magnetosheath field typically originate in the solar wind, similar analysis was performed on lagged ACE data for 1,187 events with the results shown in Figure 7.9 (middle & right). In the mean (middle), a similar discontinuity-like increase in the wavelet power is seen, largest in the z component. However the median (right) showed no such feature (neither did the null analysis). This means that the increase exhibited in the mean is due to the distribution becoming more skewed than the background distribution. Therefore,
the majority of magnetosheath dynamic pressure pulses do not show an increase in wavelet power of the solar wind magnetic field, hence are not associated with changes in the IMF. Nonetheless, there is a minority of pulses that do appear to be associated with solar wind discontinuities which cannot be explained by chance, though quantifying this fraction is difficult.

The mean background total wavelet power in the solar wind, shown in Figure 7.10, is typically smaller for the pulses than that for the null events. Thus during periods of magnetosheath dynamic pressure pulses, the IMF is generally steadier than usual. Since the pulses are predominantly found downstream of the quasi-parallel shock, this suggests that a stable foreshock is important in the generation of the majority of magnetosheath dynamic pressure pulses.

7.6. Discussion and conclusions

In this chapter, the first comprehensive statistical study of large amplitude, transient enhancements of the magnetosheath dynamic pressure has been presented. Pulses with durations 10 s to 3 mins were observed, consistent with previous studies [e.g. Němeček et al., 1998; Savin et al., 2008], with ~25% of them showing at least 200%
increases in the dynamic pressure. The dynamic pressure transients are most often dominated by velocity increases and the density can either increase or decrease, broadly separating the pulses into two different regimes.

Those with density decreases are much less frequent (18% of all pulses) and are typically consistent with FTEs at the subsolar magnetopause under southward, high cone angle IMF. On the other hand, previous case studies have identified dynamic pressure pulses in the magnetosheath containing depressions in the density which could not be attributed to reconnection [Shue et al., 2009; Hietala et al., 2009]. It therefore appears that such events are not very common.

In contrast, pulses containing increases in the density are by far the most common, though the fractional increase in density is usually small. They are characterised by a decrease in the ion temperature but slight increase in thermal pressure and a small velocity deflection to smaller cone angle. On average the deflection is only a few degrees larger than the ambient plasma, consequently the large increases in flow speed are not likely explained by the bow shock ripple ideas proposed by Hietala et al. [2009, 2012]. The flow is also highly super-Alfvénic hence cannot be attributed to reconnection. However, the typical properties presented cannot unambiguously distinguish the predominant origin of the pulses from those previously proposed.

The dynamic pressure pulses with density increases predominantly occur under low cone angle IMF, in contrast to those with density decreases. In general, pulses of both types are most frequent throughout the quasi-parallel magnetosheath and are therefore likely to be generated at or near the shock, in agreement with previous results [e.g. Němeček et al., 1998; Hietala et al., 2009] and those in chapter 6. On the other hand, those downstream of the quasi-perpendicular shock are most often observed close to the magnetopause. These include the previously identified FTEs and could also consist of jets/pulses deflected or reflected by the magnetopause, as previously shown by Amata et al. [2011], or accelerated flows near the plasma depletion layer. It is also found that pulses are more frequent with decreasing zenith angle and increasing solar wind speed; though no clear dependence on IMF clock angle, solar wind plasma $\beta$ or Mach number could be found. Hence it is unlikely that the pulses reported here can be explained by “magnetic slingshot” effects [Chen et al., 1993; Lavraud et al., 2007; Lavraud and Borovsky, 2008], which predominantly occur downstream of the Earth under low Mach number solar wind and northward IMF. The reasons for the trends presented here are unclear at present and require
further investigation.

Solar wind discontinuities feature in a number of previously proposed origins of magnetosheath dynamic pressure pulses [e.g. Lin et al., 1996a, b; Savin et al., 2011, 2012]. However, it seems that whilst some (more than can be explained by chance) are associated with changes in the IMF, these are in the minority. In fact during periods of magnetosheath dynamic pressure pulses, the IMF is typically steadier than usual. Němeček et al. [1998] postulated that foreshock discontinuities could interact with the shock in an analogous way to the simulations of those originating in the solar wind [e.g. Lin et al., 1996a]. Such foreshock discontinuities/structures could be the origin of the observed sharp changes in the magnetosheath magnetic field. It is likely that such structures require a stable foreshock in order to develop and therefore a steady quasi-radial IMF. Therefore, it might be that foreshock structures/processes are important in the generation of the majority of magnetosheath dynamic pressure pulses. Hybrid or kinetic simulations could provide insight into the downstream signatures of foreshock structures and how they compare with the typical properties of the dynamic pressure pulses reported here. Furthermore, multipoint observations immediately upstream and downstream of the quasi-parallel shock may also aid in understanding the physical processes resulting in these pulses in the magnetosheath. Since the effective pressure on the magnetopause is typically significantly enhanced by these structures, these pulses may have magnetospheric effects. This topic is the subject of the next chapter.
8. Magnetospheric Response to Dynamic Pressure Pulses


8.1. Introduction

It has been established in chapter 6 and chapter 7 that dynamic pressure pulses in the magnetosheath enhance the total pressure acting on the magnetopause. In general, upstream pressure variations can perturb the magnetopause, enhance the magnetospheric field, excite direct and resonant waves (often in the Pc5 range i.e. 2-7 mHz) in the magnetosphere, and generate travelling convection vortices (TCVs) in the ionosphere [e.g. Sibeck, 1990; Hartinger et al., 2013, and references therein], as detailed in chapter 4. Thus dynamic pressure pulses have the potential to impinge upon the boundary and have effects within the magnetosphere.

Shue et al. [2009] and Amata et al. [2011] showed that individual magnetosheath jets were able to distort and move the magnetopause ~0.5-1.5 $R_E$. Irregular magnetic pulsations at geostationary orbit and localised flow enhancements in the ionosphere were reported by Hietala et al. [2012] to be caused by jets under steady quasi-radial IMF. These “mesoscale” ionospheric signatures shared some similarities with Magnetic Impulse Events (MIEs) and TCVs, though they did not appear to travel. In contrast, Dmitriev and Suworova [2012] showed that a plasma jet due to a solar wind discontinuity resulted in a large-scale magnetopause distortion of an expansion-compression-expansion sequence lasting ~15 min; effective penetration of magnetosheath plasma inside the magnetosphere; and travelling ground magnetometer signatures at low to mid latitudes over much larger spatial scales. They
were unable to explain, however, why the discontinuity of duration \( \sim 1 \text{ min} \) resulted in a much longer timescale in the response.

One possible explanation for longer timescale responses might be due to the characteristic period of magnetopause perturbations about equilibrium from damped harmonic oscillator models of the boundary \cite{Smit1968, Freeman1995, Børve2011}. These yield characteristic periods ranging from 2-12 min though typically about 6 or 7 min and, due to strong damping, the magnetopause is thought to act somewhat like a low pass filter to pressure variations. Therefore, pressure variations in the magnetosheath can be used to test these models’ predicted magnetospheric response. \textit{Glassmeier et al.} \cite{Glassmeier2008} showed that when the subsolar magnetosheath pressure varies on timescales of 5-7 minutes with amplitudes \( \sim 0.5 \text{ nPa} \) (\( \sim 50\% \) the ambient value) the magnetopause motion and compression/expansion of the magnetospheric magnetic field are quasistatic. In contrast, the transient magnetosheath dynamic pressure pulses of this thesis are on much shorter timescales (around 30 s as shown in chapter 7) than those of expected magnetosheath motions and are quasi-periodic, recurring on timescales of a few minutes (as shown in chapter 6).

Whilst it is evident that magnetosheath pressure pulses can cause magnetopause motion, their subsequent effects and how these relate to other magnetospheric phenomena are not well understood. The response to quasi-periodic pulses, as opposed to isolated ones, is also unclear. Here the study of chapter 6 is continued, using a comprehensive chain of observations from the magnetosheath to the ground during the periods of magnetosheath dynamic pressure pulses in order to study their magnetospheric response. While individual magnetosheath pulses are sharp and impulsive, the magnetospheric response is found to be much smoother with frequencies in the Pc5-6 range being excited in the compressional and poloidal components of the magnetic field. The magnetopause does indeed act like a low pass filter, suppressing timescales shorter than a few minutes. Further filtering appears to occur locally within the magnetosphere, which may be due to the unusual field line resonance frequency profile on this day. Ground magnetometer and radar data along with equivalent ionospheric currents show signatures of travelling convection vortices, similar to the response from pressure variations of solar wind origin. However, the signatures are associated with groups of magnetosheath pulses rather than individual ones due to the impulsive nature of the pressure variations. Thus the scale-dependent magnetospheric response to these transient pressure variations, results in
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The positions of the THEMIS and GOES spacecraft on 30 September 2008 are shown in Figure 6.1. THD and THE, separated by $\sim 1 \text{ R}_E$, provided observations of the magnetosheath pressure between 15:01 UT and 22:47 UT revealing periods of dynamic pressure pulses. THA was initially in the magnetosheath but travelled earthward into the magnetosphere. Additional outer magnetospheric observations come from three GOES spacecraft (G10, G11 and G12) at geostationary orbit.

8.2.1. Observations

8.2.1.1. Plasma Observations

THA crossed the magnetopause into the magnetosphere, close to the subsolar point, at 17:01 UT (Figure 8.1b-f). Several oscillations of the magnetopause surface were observed between 17:01-17:04 UT, as seen in the ion energy spectrogram (panel Figure 8.1b) and ion density (panel Figure 8.1d). During the period depicted in Figure 8.1, THA encountered Low Latitude Boundary Layer (LLBL) plasma (indicated by the orange bars), identified by the heated electrons (panel Figure 8.1f), a mixture of high energy magnetospheric ion populations and diluted magnetosheath plasma (panel Figure 8.1b) and bidirectional streaming electrons (not shown) [McFadden et al., 2008b, c]; cold ion populations of the order of a few eV (purple bars) as have been observed in the vicinity of the magnetopause before, which are detected due to the convective electric field associated with boundary motion allowing ions to overcome the spacecraft potential [e.g. Sauvaud et al., 2001; McFadden et al., 2008d]; and the cold and dense plasma sheet (CDPS), a mixture of magnetosheath and magnetospheric ions and an absence of heated electrons, as previously reported by Øieroset et al. [2008] due to either dual-lobe or tailward-of-the-cusp reconnection (grey bar).

At around $\sim 17:08 \text{ UT}$, THD and THE observed a pressure pulse in the magnetosheath (panel Figure 8.1a). A couple of minutes preceding this pulse THA observed a decrease in energy flux of heated ions and electrons with an increase in coherent signatures on longer timescales than any individual pulse.
magnetosheath-like ions. The ion velocity moment from ESA (panel Figure 8.1c) showed a signature of motion consistent with the magnetopause moving due to the action of the pressure pulse i.e. anti-sunward ion motion followed by sunward. The timings are consistent with the expected lag between the spacecraft, given the approximate orientation of the discontinuities (see Figure 6.1) and the associated error in this lag, thereby suggesting that the pressure pulse impinged upon the magnetopause.

Another pressure pulse was observed by both THD and THE at around 17:33 UT. A few minutes preceding this THA, previously in the magnetosphere proper, observed LLBL plasma sandwiched by cold ion populations. There is good agreement between the duration of this LLBL plasma and that of the pressure pulse. This can be interpreted as further motion of the magnetopause in response to the pressure pulse impacting upon it, such that only the LLBL plasma and cold ions were observed.
Later between 18:30-19:10 UT, when THA was \( \sim 0.8 - 1.2 \) \( \text{R}_\text{E} \) from the initial magnetopause crossing in the GSE x direction, a series of three cold ion populations were again observed, with a number of velocity oscillations anti-sunward followed by sunward. Two of these ion populations were detected as increases in the density by ESA. The duration and times of the cold ion populations show fairly good agreement with the large amplitude dynamic pressure enhancements observed by THD and THE. Despite these pressure pulses being larger in amplitude than the previous two mentioned, THA was further away from the magnetopause therefore the motion of the magnetopause under the action of the pulses caused only the cold ions to be detected i.e. the magnetopause motion was such that THA did not enter the LLBL or cross the magnetopause itself. It is interesting to note that these three magnetopause motions were associated with groups of pulses rather than individual ones.

These events all support the hypothesis that the magnetosheath pressure pulses presented here can distort the magnetospheric boundary, as has been previously shown \[Shue et al., 2009; Amata et al., 2011; Dmitriev and Suvorova, 2012\]. While models suggest that typical timescales of magnetopause motions should be around 6 or 7 minutes \[Smit, 1968; Freeman et al., 1995; Børve et al., 2011\], the pressure pulses are much more abrupt and it appears that their quasi-periodicity also leads to an aggregate response of the magnetopause due to groups of pulses.

### 8.2.1.2. Magnetic Field Observations

Magnetic field data from THA and the GOES spacecraft was transformed into a mean field aligned coordinate system (MFA) with the field aligned component \( \mathbf{F} \) (given by a 20 minute moving average) representative of compressional modes; the azimuthal component \( \mathbf{A} = \mathbf{F} \times \mathbf{r} \) (where \( \mathbf{r} \) is the spacecraft’s geocentric position, thus \( \mathbf{A} \) points east) representative of toroidal Alfvénic modes; and the radial component \( \mathbf{R} \) (completing the right-handed set pointing towards the Earth) representative of poloidal Alfvénic modes. Figure 8.2 shows the changes in the field aligned component (black) observed by THA and the three GOES spacecraft along with the magnetosheath total pressure observations in the top panel. In all panels the spacecraft positions are indicated in the horizontal axes by their magnetic local times (MLT) and, for the magnetospheric spacecraft, L-shells. So that observed fluctuations are clearer, the predicted field magnitude from the T96 geomagnetic field
model [Tsyganenko, 1995; Tsyganenko and Stern, 1996] using average upstream conditions has been subtracted. This is a semi-empirical best-fit representation of the geomagnetic field, based on a large number of satellite observations (IMP, HEOS, ISEE, POLAR, Geotail, GOES etc.) which include the contributions from major external magnetospheric sources: ring current, magnetotail current system, magnetopause currents, and large-scale system of field-aligned currents. Whilst it is not a perfect representation of the geomagnetic field, thus large offsets and long term trends in Figure 8.2 should be ignored, it does predict the main field fairly well. THA data is only shown between 18:00-22:00 UT, due to the LLBL crossings before then (Figure 8.1) and afterwards the magnetic field direction was changing faster than the averaging period, resulting in a poor estimate of $F$.

Using the magnetosheath total pressure measurements as input to the T96 model, the predicted quasistatic response of the magnetosphere to pressure variations at the spacecraft locations can be found as shown in Figure 8.2 (grey) using THD data. During intervals without pulses, the compressional variations of the magnetospheric field were similar to these predictions (with some systematic differences due to the statistical nature of the T96 model), consistent with Glassmeier et al. [2008]. It is clear, however, that the response to the pulses (highlighted by the magenta bars) was different since the observed compressions of $\sim$1-10 nT (similar to those of Hietala et al. [2012] and Dmitriev and Suvorova [2012]) were much weaker and smoother than the sharp and impulsive magnetosheath pressure variations. Figure 8.2 also indicates a hot flow anomaly at around 19:15 UT which shall be discussed later in this chapter.

### 8.2.2. Analysis

Although the magnetosheath pressure pulses contained variations over a wide range of frequencies due to their short timescales and quasi-periodicity, the harmonic oscillator models of the magnetopause [Freeman et al., 1995; Børve et al., 2011] predict a response somewhat like a low pass filter with a typical timescale of about 6 or 7 mins. Therefore the THD magnetosheath total pressure measurements were smoothed by a 6 minute running average (THE yielded qualitatively similar results) before being input into the T96 model, giving more realistic predictions which are shown in Figure 8.2 (red). The predicted responses to the pulses, which could not be accounted for simply by the solar wind pressure variations shown in Figure 6.7, show
good agreement with the magnetospheric observations overall. For the periods of pulses between 18:30-19:05 UT, the prediction yields three compressions of similar amplitude to those observed by THA and G11. THA also observed some higher frequencies which the smoothing does not capture e.g. the two peaks in the 18:35 UT compression corresponding to two individual magnetosheath pressure pulses. These
features were not as prominent at geostationary orbit, consistent with further filtering occurring at progressively lower L-shells. Between 21:00-23:00 UT, G11 and THA (when applicable) observations showed further agreement with the predictions (G10 and G12 were close to dusk during this period) though underestimated the response by $\sim$0.5-1 nT. Around 17:00 UT the agreement was less clear, though both signatures were small at less than $\sim$0.5 nT.

The predictions made through smoothing the magnetosheath pressure highlight the collective effect of pulses: the magnetospheric responses occurred over longer timescales and were due to many pulses rather than individual ones. This furthers the suggestion of Hietala et al. [2012] that pulses may have cumulative effects and that a one-to-one correspondence between individual pulses and their effects is not always clear. The filtering effect of the magnetopause may also account for the 15 min period response reported by Dmitriev and Suvorova [2012] due to a $\sim$1 min magnetosheath jet associated with a discontinuity, though the origin of the expansion-compression-expansion signature for that event is not clear since the magnetosheath pressure was only observed during the jet.

8.2.2.1. Time-Frequency Analysis

Whilst a characteristic period of about 6 min is thought to be associated with the magnetopause, the local relevant timescale within the magnetosphere is that of field line resonances (FLRs) and these were estimated using the time of flight approximation

$$f_{\text{FLR}} = \left[ 2 \int \frac{ds}{v_A} \right]^{-1}$$

(8.1)

where $f_{\text{FLR}}$ is the fundamental FLR frequency, $v_A$ is the Alfvén speed and the integration is carried out over the entire length of the field line. Note that no distinction is made between poloidal and toroidal mode FLRs in this calculation, though they are typically similar [Cummings et al., 1969]. The average T96 model was used along with a power law density distribution along the field line [Radoski and Carovillano, 1966]

$$\rho(L, r) = \rho_0(L) \left( \frac{L}{r} \right)^m$$

(8.2)
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where $r$ is the geocentric radial distance, $L$ is the equatorial distance to the field line, $\rho_0(L)$ is the equatorial mass density and the exponent $m$ is taken to be 2 [Denton et al., 2002; Clausen et al., 2009]. Since THA travelled from the magnetopause to the inner magnetosphere close to the equatorial plane, $\rho_0(L)$ can be determined using Equation 8.2 and the spacecraft potential inferred density [McFadden et al., 2008b] shown in Figure 8.3. Unlike the standard magnetospheric density profile which shows a sharp jump in density at the plasmapause, the wave implications of which have been modelled extensively [e.g. Lee and Lysak, 1989], THA observed a steady increase in electron density of four orders of magnitude from $L \sim 9.5$ similar to that reported by Tu et al. [2007] during magnetospheric quiet times. In the calculation the density was smoothed using a 20 minute running average to remove fluctuations and the atomic mass was assumed to be 1. Assuming $\rho_0(L)$ did not change significantly over this interval, the FLR frequencies were also estimated for the GOES spacecraft. The calculations resulted in $f_{FLR} \sim$0.5-6 mHz i.e. in the Pc5-6 range, though it should be noted that due to the density profile here the configuration of the FLR frequencies is rather different to those usually modelled [e.g. Lee and Lysak, 1989] as shown in Figure 4.8. The computed frequencies are consistent with those obtained by Wild et al. [2005] using a similar method which were validated against numerical solutions to the wave equations as well as observed geomagnetic pulsations. While previous studies have shown that the difference between estimated FLR frequencies using different models can be large [Berube et al., 2006; McCollough et al., 2008], here it was found that using a dipole model field changed the results by only $\sim$1 mHz at the largest L-shells and this difference rapidly became negligible with decreasing L-shell. Similarly, changing the exponent of the density distribution had little effect on the results. Thus the estimated frequencies are broadly correct, indeed in this study precise FLR frequencies are not required.

To examine the frequency content of magnetospheric pulsations during intervals of magnetosheath pulses, dynamic spectra of the magnetic field data in the MFA system were calculated using the Morlet wavelet transform [Torrence and Compo, 1998]. The wavelet transform was used, rather than Fourier methods, as it allows for variations in time whilst still giving frequency information without imposing any timescales (such as window lengths) into the analysis. A brief discussion of wavelet analysis is given in Appendix D. The results for the field aligned (with the mean field subtracted) and radial components are shown in Figure 8.4 for THA, G10 and G11 (G12 was similar to G10, an hour later in MLT) along with the
phase difference when well defined (wavelet coherence [Torrence and Webster, 1999] greater than 0.75). The estimated first three harmonics of FLR frequencies are shown as the black lines. Also shown is the expected frequency of upstream ULF waves generated in the ion foreshock [Takahashi et al., 1984] which are convected into the magnetosphere [e.g. Clausen et al., 2009], calculated from 1 min smoothed (to remove contamination from upstream waves) THB data. At the spacecraft locations this was typically distinct from the FLR frequency. Pulsations at the upstream wave frequency are seen in Figure 8.4 often coincident with periods of pulses since they occur downstream of the quasi-parallel shock (as shown in chapter 6).

Figure 8.4 shows that THA observed, between 18:30-19:05 UT, large increases in the compressional mode power at the fundamental FLR frequency and below, with much less power at higher frequencies (apart from at the upstream wave frequency). The same interval observed by the GOES spacecraft, whilst lower power, also showed the largest increases at or below their respective fundamental FLR frequencies, which were lower than for THA. Thus further filtering of the compressional component occurred at lower L-shells. This may be due to the unusual FLR frequency profile on this day, which went down with decreasing L-shell from the magnetopause.
to \( L \sim 6 \). Near the magnetopause, broadband compressional waves at timescales of \( \sim 3 \) minutes and longer would be expected due to the action of the pulses, as was observed by THA at around 18:35 UT. At progressively lower \( L \)-shells, a filtering effect suppressing frequencies greater than the fundamental FLR frequency might be due to compressional power resonantly converting to toroidal modes at the FLR frequency. It is beyond the scope of this study to discount other potential mechanisms of filtering under this unusual magnetospheric configuration. Future modelling and observational work could help distinguish between these mechanisms.

During other periods of pulses, GOES observations again showed enhancements in the power typically at or below the FLR frequency. At around 21:00 UT, THA observed enhancements in power at frequencies \( \sim 3 \) mHz which, while above the local FLR frequency, were consistent with the characteristic timescales of the magnetopause. Since there were no observations close to the magnetopause at this time it is unclear whether this response is contrary to that reported for the earlier pulses or due to other effects.

The dynamic spectra of the radial component of the magnetic field (indicating poloidal modes) were similar to the field aligned component, but contained slightly less power. The coherence between the two components at \( P_c5-6 \) frequencies was generally good and the radial component lagged the field aligned one, though the phase difference did not appear to be in perfect quadrature or even constant. The radial component of the magnetic field observed by THA between 18:30-19:05 UT was anti-correlated with the velocity fluctuations shown in Figure 8.1, consistent with poloidal Alfvén waves propagating parallel to the magnetic field.

The azimuthal component of the magnetic field contained significantly less power. Figure 8.5 shows wavelet band-pass filtered data from G10 and G11 at the first three FLR harmonics. There is some evidence of toroidal mode FLRs (typically the first and second harmonic) due to magnetosheath pressure pulses with \( \sim 0.2 \) nT amplitudes at geostationary orbit, comparable to those triggered by solar wind pressure pulses [Sarris et al., 2010]. However, frequencies consistent with FLRs were also observed during some periods without any pulses. It should be noted that the magnetic perturbations associated with the fundamental toroidal mode are expected to be weak near the magnetic equator and thus difficult to observe by the spacecraft in this study [Singer and Kivelson, 1979]. Standing waves have a \( \pm 90^\circ \) phase relationship between the electric and magnetic fields, however testing this using wavelet
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Figure 8.5.: (top panel) Magnetosheath total pressure in the same format as Figure 8.2. (subsequent panels) Stacked plots of the azimuthal magnetic field component observed by G10 and G11 which have been wavelet band-pass filtered to the first three field line resonance harmonics. Additional horizontal axes indicate the spacecraft magnetic local time (MLT).

On this day there was a notable exception to the filtered magnetospheric response to pressure variations. A sharp drop in the magnetosheath pressure was observed by THC, THD and THE at around 19:15 UT (indicated in figures by a triangle) due to a tangential discontinuity in the solar wind which satisfied the Schwartz et al. [2000] conditions for the formation of hot flow anomalies (HFAs). While no plasma data upstream of the shock was available, the magnetosheath observations were qualitatively similar to the HFA signatures reported by Eastwood et al. [2008] exhibiting flow deflections, magnetic field enhancements, density cavities and hot plasma. The magnetospheric spacecraft observed a sharp decrease in the magnetic field due to the HFA (Figure 8.2) which consisted chiefly of frequencies at or above the fundamental FLR (Figure 8.4). Further work is required to understand why the magnetospheric response to HFAs is different to those expected purely from pressure

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8.2.2.2. Transfer Function

It is possible to quantify the low pass filter response of the magnetosphere due to the simultaneous observations of both the driver (the magnetosheath pressure pulses) and the magnetospheric response. This enables an estimation of the magnetopause pressure transfer function, the frequency dependent response of the magnetopause to pressure variations in the magnetosheath. This is estimated during the periods of pressure pulses using data from THD and THA between 18:30-19:05 UT, since they were closest in MLT (just over an hour apart) and THA was only $\sim 1 R_E$ antisunward of the magnetopause. The transfer function gives an estimate of to what degree pressure balance at the magnetopause holds over different timescales. Using the wavelet transforms of the magnetosheath total pressure from THD $W_{P_{msh}^{tot}}(t,f)$ and the magnetospheric magnetic pressure from THA $W_{P_{sph}^B}(t,f)$, the transfer function $H(f)$ was calculated as:

$$H(f) = \frac{\int_{t_1}^{t_2} \left| W_{P_{sph}^B}(t,f) \right|^2 dt}{\left( \int_{t_1}^{t_2} \left| W_{P_{msh}^{tot}}(t,f) \right|^2 dt \right)^{1/2}}$$ (8.3)

Note that time averaged wavelet spectra (i.e. the integrals) are comparable to Fourier power spectral densities [Torrence and Compo, 1998] thus the transfer function here is similar to that computed using Fourier methods. The transfer function is shown in Figure 8.6(top) along with the corresponding time-averaged wavelet coherence (bottom), which can be interpreted as a local squared correlation coefficient at a given frequency.

At frequencies below the local FLR frequency, the transfer function is large ($\sim 0.5$) and the coherence is close to unity at $\sim 0.9$, hence these frequencies are transmitted and the magnetopause reacts quasistatically, consistent with Glassmeier et al. [2008]. At the lowest FLR frequency the coherence drops to $\sim 0.45$ varying by only $\sim 0.05$, implying only some correlation between the magnetosheath and magnetosphere. The transfer function above the range of FLR frequencies, however, is small at $\sim 0.05$. There is a small peak corresponding to the upstream wave frequency during this period, however no increase in coherence is observed. Since upstream waves
in the foreshock and magnetosphere are quasi-monochromatic [e.g. Clausen et al., 2009] and magnetosheath pressure pulses are highly broadband, it is unlikely that the pulses are the mechanism by which foreshock ULF waves propagate through the magnetosheath. Song et al. [1993] suggested that the pressure variations associated with compressional waves in the magnetosheath cause the magnetopause to oscillate and reported that 17% of the Pc3-4 wave energy was transmitted across the magnetopause. The waves in their study had a frequency of \( \sim 10 \) mHz, which according to the transfer function here corresponds to \( \sim 5\% \) transmission. Since the magnetospheric observations here are further from the boundary (\( \sim 1 \) RE) the results here are not inconsistent with theirs.

The red dashed lines in Figure 8.6 show the frequency response and coherence of a 6 minute running average. These are somewhat similar to the observations with some notable differences: at frequencies above \( \sim 20 \) mHz the running average underestimates the transfer function and the peak in the coherence of the running average

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**Figure 8.6.** Estimate of the magnetopause pressure transfer function (top) and corresponding coherence (bottom) during the 18:30-19:05 UT magnetosheath pulses. The red dashed lines indicates the theoretical frequency response of a 6 minute running average using the same method. Dotted blue lines indicate the range of field line resonant (FLR) frequencies over the interval used, with the light blue area also incorporating the spectral width of the Morlet wavelet. The magenta dotted line shows the average frequency of upstream waves (UW) during this interval, with the light purple area again indicating the width of the wavelet.
at \(\sim 5\) mHz is not observed. Therefore, whilst a 6 minute running average does not precisely capture the response of the outer magnetosphere to the pressure variations, it nonetheless provides a reasonable first approximation.

8.3. Ground Magnetometers

8.3.1. Observations

The times of the magnetosheath pressure pulses were such that many ground magnetometer (GMAG) stations across North America were on the dayside (THEMIS, CARISMA, CANMOS, MACCS, GIMA, DTU, USGS and STEP). Figure 8.7 displays examples from latitudinally separated (\(\sim 50^\circ\) and \(60^\circ\) geomagnetic latitude) stations close to 12:00 MLT where the D (mean magnetic east) and H (mean magnetic north) components with the 2 hour linear trend removed are shown (grey) along with 6 minute smoothed data (black). Time lags (between \(\sim 3-10\) minutes) have been applied manually to the magnetosheath data to approximately align with the GMAG data since accurately calculating such lags is difficult.

Ionospheric Hall currents rotate magnetic pulsations by approximately 90° [Hughes, 1974; Hughes and Southwood, 1976a, b], as explained in subsection 4.2.3, hence the D component should chiefly contain poloidal mode waves, linked to the magnetospheric compressions. Indeed at TPAS, \(B_D\) was very similar to the compressions observed by THA (compare with Figure 8.2). The lower latitude PINE station observed smaller amplitudes and a much smoother response. This smoothing effect is similar to that noted when comparing THA observations to GOES. During the other periods of magnetosheath pressure pulses, there was some agreement with the variations in the D component and the smoothed magnetosheath pressure with some evidence of higher frequencies (other than the upstream wave frequency) being transmitted but suppressed, similar to the spacecraft observations. These features were observed by all dayside GMAGs, though the amplitude of the pulsations and their relative frequency content varied significantly between stations. Variations in the H component were unlike the D component, though they were found to resemble its negative time derivative e.g. at 18:35 UT TPAS observed a positive excursion in the D component and a negative-positive bipolar signature in the H component. Such a relationship is often associated with travelling convection vortices [e.g. Glassmeier
8.3 Ground Magnetometers

Figure 8.7: (top) Magnetosheath total pressure as measured by THD (turquoise) and THE (blue). The black line shows the THD measurements smoothed by a 6 minute running average. The applied time lags for the three panels are indicated and a HFA is highlighted by the downward pointing triangle. (subsequent panels) Stacked plots of GMAG data near the subsolar point. Grey lines show the detrended D (middle) and H (bottom) components of the field, with 6 minute smoothed data shown in black. Station names, geomagnetic latitudes and the average magnetic local time are indicated.

et al., 1989].

8.3.2. Analysis

To quantify the varying amplitudes of features and their relative timings, GMAG B_D observations were binned by magnetic longitude and the time intervals containing the response to groups of pulses were manually identified. The two hour linear trend was removed from the time series and the time and amplitude of the largest peak within this interval was then found. The results for the group of pulses around 18:35 UT are shown in Figure 8.8 (those for around 18:50 UT proved similar), where the amplitudes are indicated by the size of the circles and their relative timings are given by the colours. It is clear that the signatures tracked westwards. The longitudinal speed of the response, calculated from a least-squares linear fit of the high latitude data, was found to be 9±2 km s⁻¹. Assuming events propagate through
Figure 8.8.: Map of North America in geomagnetic coordinates (Magnetic Local Time along the horizontal and geomagnetic latitude Λ along the vertical) showing the response to the period of magnetosheath pulses at around 18:35 UT. GMAG stations are indicated by circles, where the amplitude of the observed pulsation in the D component is indicated by its size and their relative timings are given by the colours. The footprints (from the T96 model) of the spacecraft are shown as crosses and the field of view of the Rankin radars are given by the green area. The GMAG stations used in Figure 8.7 are also highlighted.

The ionosphere and magnetosphere with a constant angular velocity [Korotova et al., 2002], this corresponds to a velocity of 245±25 km s\(^{-1}\) at the magnetopause nose. The velocity along the normal of a rotational discontinuity in the solar wind is

\[v_n = \mathbf{v}_{sw} \cdot \mathbf{n} + v_A\]  \hspace{1cm} (8.4)

where \(\mathbf{v}_{sw}\) is the solar wind velocity vector, \(v_A\) is the Alfvén speed and the normal \(\mathbf{n}\) (see Figure 6.1) was estimated by the cross product method [e.g. Knetter et al., 2004]. Sibeck et al. [2003] argue that pressure variations approximately retain their solar wind alignment in the magnetosheath since the sum of the fast mode and convection velocities are of the order of the solar wind speed. This approximation allows for an estimation of the speed at which the discontinuities, and thus the pulses that were associated with them, swept across the magnetopause. The component of the discontinuities’ velocity \(v_n\) in the westward direction was found to be 260 km s\(^{-1}\) (assuming a tangential discontinuity, where \(v_n = \mathbf{v}_{sw} \cdot \mathbf{n}\), only reduces this estimate by \(\sim 25\) km s\(^{-1}\)), consistent with the estimate from the ground signatures. These
results are comparable to Dmitriev and Suvorova [2012] who showed low- to mid-
latitude GMAG signatures due to a single magnetosheath jet whose locations were
consistent with the transition in shock geometries of a solar wind discontinuity and
whose relative timings were in fair agreement with the discontinuity’s motion.

The amplitude of the ground signatures not only increased with magnetic latitude
but also towards the west e.g. at 65° geomagnetic latitude it varied from $\sim$5 nT
at 15:00 MLT to $\sim$30 nT at 07:30 MLT. This may be because the morning sector
corresponded to a more quasi-parallel bow shock and thus perhaps larger pressure
variations. Whilst such pulses are known to be most prevalent downstream of the
quasi-parallel shock (as demonstrated in chapter 7), the factors that control their
amplitude are unknown. Nonetheless, it is generally known that magnetopause
motions and magnetic pulsations are greater pre-noon rather than post-noon, cor-
responding to the location of the quasi-parallel bow shock under Parker spiral IMF
[e.g. Sibeck, 1990]. There are of course many other factors which may affect the
observed amplitudes on the ground including azimuthal wave number, frequency,
density distribution along field lines and ionospheric conductivity [e.g. Sciffer and
Waters, 2011].

Wavelet analysis was also performed on the D and H components of the GMAG
data. The results were similar to the spacecraft data in Figure 8.4, with enhanced
Pc5-6 frequencies during periods of magnetosheath pressure pulses. The peaks in
the spectra during the pulses, while at different powers depending on latitude and
MLT, were at the same frequencies for all stations, therefore, there was no evidence
of L-shell dependent FLRs observed on the ground.

8.4. Ionosphere

8.4.1. Equivalent Ionospheric Currents

GMAG data can be used to calculate ionospheric currents using the spherical elemen-
tary current system method developed by Amm and Viljanen [1999]. The technique
defines two elementary current systems: a divergence-free elementary system with
currents that flow entirely within the ionosphere and a curl-free system whose diver-
gences represent the field aligned currents (FACs). The superposition of these two
elementary current systems with different weights or scaling factors can reproduce
any vector field on a sphere. Thus the ionospheric currents can be estimated over an area by inverting Ampère’s Law applied to observations from GMAG networks. Weygand et al. [2011] have applied this method to the GMAGs across North America and Greenland, finding that close to GMAG stations the derived currents were accurate to as good as 1% whereas in low coverage areas this was around 15%.

Figure 8.9: (top) Magnetosheath total pressure as measured by THD (turquoise) and THE (blue). (bottom) Feather plot of equivalent ionospheric currents at one grid point (with geomagnetic latitude 71° and the magnetic local time indicated in the horizontal axis) as a function of time, where geomagnetic north points upwards and geomagnetic east to the right. The horizontal current magnitude is shown in red. Data provided by J. M. Weygand.

J. M. Weygand provided Equivalent Ionospheric Currents (EICs) from the Weygand et al. [2011] database for this day. An example time series of EICs during magnetosheath pressure pulses is shown in Figure 8.9, taken at 71° geomagnetic latitude and around 12:00 MLT between 18:30-19:30 UT. This grid point was only ~310 km away from a GMAG station, therefore the EICs are likely reliable. During the periods of magnetosheath pulses there were enhancements in the horizontal currents (red). The directions of the currents showed two counterclockwise rotations between 18:30-19:10 UT. These signatures tracked westwards like the magnetic deflections observed by the GMAGs. Assuming that ionospheric currents are composed mainly
of Hall currents, EICs can be used as an approximation to the plasma convection. Weygand et al. [2012] showed that in general the EICs derived from this method are anti-parallel to the flows observed by the SuperDARN radars. Therefore, the counterclockwise rotations in Figure 8.9 are consistent with pairs of travelling convection vortices (TCVs), where the vortex centres were north of the grid point (compare with Figure 8.10). Such pairs of vortices are expected from transient compressions of the magnetopause as they generate a pair of field-aligned currents which in turn have associated Hall current vortices [e.g. Sibeck et al., 2003]. The timescales of these TCV signatures were close to the peak of the distribution of TCVs by Clauer and Petrov [2002]. Current enhancements and signatures consistent with TCVs were again seen in the EICs between 21:00-22:00 UT (not shown) which corresponded to groups of magnetosheath pulses, however, this association was less clear at 17:00 UT due to a following decrease in the solar wind pressure. During periods without magnetosheath pressure variations, the directions of the EICs remained fairly steady thus did not exhibit TCV signatures.

Figure 8.10.: (top) Illustration of the current field surrounding a pair of vortices (clockwise followed by counterclockwise). In the vortex frame a grid point cuts through the structures travelling east (grey arrow). (bottom) Corresponding feather plot of the current at the grid point (c.f. Figure 8.9).

Figure 8.11 shows maps of the EICs, where panel (a) is an example of the currents without magnetosheath pressure pulses and panels (b)-(d) show the responses to three groups of pulses. Contours of the current magnitude are shown as the colours whereas its direction is given by the arrows (which are generally smoothly varying suggesting they are reliable). The current was enhanced due to the groups of pulses most prominently at around 70° geomagnetic latitude and above (red areas
in Figure 8.11). This is consistent with the occurrence distribution of Magnetic Impulse Events (MIEs) often associated with TCVs [e.g. Moretto et al., 2004]. Note that the number of magnetometers (pink squares) at these high latitudes is however small. The scale sizes of the current enhancements ranged from around 30° in magnetic longitude up to almost the entire dayside. It is helpful to convert timescales at the magnetopause into transverse scale sizes. Since it has been assumed that the discontinuities retained their solar wind alignment, the responses of ~3-10 minutes in the outer magnetosphere correspond (through multiplying by the solar wind speed) to scale sizes along the Sun-Earth line of ~13-42 R_E. Subsequently using the discontinuities’ orientation yields transverse scale sizes at the magnetopause of ~8-27 R_E i.e.~30-160° magnetic longitude. Therefore, the scale sizes of the current enhancements are consistent with the timescales on which the magnetopause responds. The vortical structure associated with TCVs is not clear from the EIC maps, likely because the vortex centres were at higher latitudes than the locations of the majority of GMAG stations.

The response to the magnetosheath pressure pulses provided by the EICs is consistent with the understood coupling between the magnetopause and ionosphere, discussed in subsection 4.2.4, within the context of the spacecraft observations. Since it has been shown that the magnetopause responds on longer timescales than individual pulses hence moves under the action of groups of pulses, the field-aligned currents associated with the localised distortion of the boundary generate TCVs that are also associated with these groups of pulses. Therefore this aggregate response to magnetosheath dynamic pressure pulses, which is otherwise similar to the known response to solar wind pressure variations, was observed not only in the magnetopause motion and geomagnetic field responses but also in the ionospheric currents.

8.4.2. Radar Observations

While EICs provide an approximation to plasma convection in the ionosphere, hence the TCV interpretation of the resulting current vortices, it is interesting to see if the motion of the ionospheric plasma in response to the magnetosheath pressure pulses can be observed directly. The Super Dual Auroral Radar network (SuperDARN) uses radars to measure the line-of-sight component of the ionospheric $\mathbf{E} \times \mathbf{B}$ drift [Greenwald et al., 1995] and on this day data was available from radars at Rankin and Inuvik. This data was provided and analysed by T. K. Yeoman. Figure 8.12
Figure 8.11.: (top) Magnetosheath total pressure as measured by THD (turquoise) and THE (blue). Black vertical lines indicate the times corresponding to subsequent panels. (a)-(d) Maps of North America in geomagnetic coordinates (Magnetic Local Time along the horizontal and geomagnetic latitude $\Lambda$ along the vertical). The magnitude of equivalent ionospheric currents are given by the colour scale and their direction are shown by the arrows. Magnetometer stations used in calculating the currents are indicated by pink squares. Data provided by J. M. Weygand.
shows data from the Rankin radars (at around 10:15 MLT) in 4 beam directions between 16:15-17:15 UT (see Figure 8.8 for the field of view). Enhanced flows were observed in a number of beam directions and in at least one beam a reversal of line-of-sight velocity. The enhancements were typically strongest between 78-82° geomagnetic latitude, though coverage above this latitude was poor. Comparing these observations with the closest GMAGs showed them to correspond to the magnetic signatures of the pulses shown in Figure 8.7(left). The flow structures propagated westwards (indicated by the arrow), seen from the relative timings at different beam directions (beam number increases towards east). Thus SuperDARN directly observed a TCV (very similar to that reported by Engebretson et al. [2013]) due to a group of magnetosheath pressure pulses. While for other groups of pulses further flow structures were observed, the data quality and coverage were often poor and the azimuthal propagation between beam directions was not clear.

![Figure 8.12.](image)

**Figure 8.12.** SuperDARN observations by the Rankin radars for a number of different beam directions (beam number increases towards east) within the field of view shown in Figure 8.8. The colour shows the ionospheric line-of-sight velocity as a function of geomagnetic latitudes $\Lambda$. The black arrow indicates the relative motion of the observed flow structure between beam directions i.e. westward. Provided by T. K. Yeoman.
8.5. Discussion and Conclusions

In this chapter, the impact of large amplitude, transient dynamic pressure pulses in the magnetosheath has been investigated using observations from the magnetopause to the ground. The pulses impinged upon the magnetopause causing its motion and triggered compressional and poloidal mode waves in the outer magnetosphere typically in the Pc5-6 range. Solar wind pressure variations have similar effects [e.g. Sibeck, 1990], though these variations are generally on comparable timescales to their responses. In contrast, the magnetosheath pulses are sharp, impulsive and quasi-periodic meaning they are much more broadband. Thus the magnetopause and (on the day considered here) lower L-shells process these variations resulting in much smoother responses with longer periods which are a collective effect of numerous pulses. This magnetospheric low pass filter suppresses frequencies much higher than those characteristic to the magnetopause and local field line resonances, consistent with the suggestions of models [Smit, 1968; Freeman et al., 1995; Børve et al., 2011].

The GMAG networks in North America allowed sampling over a large range of geomagnetic latitudes and magnetic local times. Signatures due to groups of pulses were observed in the D component, which travelled westwards (i.e. tailward in the morning sector) at a speed in agreement with the solar wind discontinuities (associated with the pulses) sweeping across the magnetopause. The H component of the field varied like the negative time derivative of the D component, consistent with travelling convection vortices [e.g. Glassmeier et al., 1989]. Equivalent ionospheric currents (EICs) also showed TCV signatures due to groups of pulses, assuming that the EICs consisted mostly of Hall currents. In addition SuperDARN observations clearly showed TCV signatures due to one period of magnetosheath pulses. Therefore, the filtered response at the outer magnetosphere to a number of magnetosheath pressure pulses can collectively generate a pair of TCVs in the ionosphere. Hietala et al. [2012] presented SuperDARN data during an interval containing many magnetosheath jets, showing localised flow enhancements which were similar to TCVs but did not appear to travel. The differences between those observations and ours are likely due to the different mechanisms generating these pulses: they were not associated with solar wind discontinuities and the authors proposed the jets were due to ripples in the bow shock under steady quasi-radial IMF. This may explain their smaller scale sizes and why they did not travel tailward due to solar wind convection.
It was shown in chapter 7 that the majority of dynamic pressure enhancements in the magnetosheath were not associated with discontinuities in the solar wind and that the IMF was indeed steadier than usual during periods of pulses, suggesting that foreshock structures and processes are important in their generation. Recently, Hartinger et al. [2013] showed that transient ion foreshock phenomena can be a source of Pc5 waves in the magnetosphere. Since the response to magnetosheath dynamic pressure pulses here were also typically in the Pc5-6 range, perhaps the signatures of transient ion foreshock phenomena in the magnetosheath contain similar pressure pulses. Further work could investigate this hypothesis.

Finally, an interesting point is the difference in the magnetospheric response to the pressure pulses and the HFA. While models suggest that the magnetopause can only respond to pressure variations on timescales of the order of minutes or longer, consistent with the response to the pulses, the impact of the HFA was on much shorter timescales, though this was in agreement to previously reported events [e.g. Eastwood et al., 2008; Jacobsen et al., 2009]. The reason for the different temporal responses between the two transient phenomena could be addressed in the future.
9. Conclusions & Prospects for Future Work

While the average properties of the space plasma environment around the Earth, the magnetosphere, have been fairly well known for some time, the system is highly dynamic. Changes in the pressure and interplanetary magnetic field (IMF) buffeting the magnetosphere regularly occur and waves and non-linear structures which originate in the foreshock are also convected toward the magnetosphere. These transients can subsequently have significant effects within the magnetosphere. It is, however, the conditions at the magnetosheath immediately upstream of the magnetopause boundary that are important, as it is here where solar wind mass, energy and momentum can be transferred to the magnetosphere. Often our understanding of the conditions driving the magnetosphere are taken far upstream of the Earth at the L1 Lagrangian point which are then suitably time lagged, but our understanding of the complicated solar wind - bow shock interaction can fail to capture important transient processes. The aim of this thesis was thus to further the understanding of the origins, occurrence, properties and impacts of one such type of transient phenomena known to occur in the magnetosheath, dynamic pressure pulses, and thus illuminate dayside magnetospheric dynamics generally. Such work necessitates the use of multipoint observations and the five THEMIS spacecraft have proven invaluable in this respect.

In chapter 6 a case study of magnetosheath pressure pulses was presented. The multipoint observations in the downstream region showed that these structures have dimensions $\sim 1 \text{ R}_E$ parallel to the flow, consistent with previous estimates, but that their extent perpendicular to the flow was $\sim 0.2-0.5 \text{ R}_E$ since notable differences were observed between spacecraft. Simultaneous observations in the pristine solar wind, foreshock and magnetosheath proved that no similar dynamic pressure variations existed upstream of the shock and that the majority of pulses were downstream of the quasi-parallel shock. By considering previously suggested mechanisms for their
Chapter 9 Conclusions & Prospects for Future Work

generation, it was shown that the pressure pulses could not be caused by reconnection, hot flow anomalies, or SLAMS and that at least some of the pressure pulses appeared to be consistent with previous simulations of solar wind discontinuities interacting with the bow shock. These simulations predict large-amplitude pulses when the local geometry of the shock changes from quasi-perpendicular to quasi-parallel, while the opposite case should also produce notable pulses but typically of lower amplitude. Therefore, in a given region of the magnetosheath, some of the discontinuities in the solar wind should generate pressure pulses, whereas others are expected not to.

The first comprehensive statistical study of dynamic pressure pulses in the magnetosheath was presented in chapter 7, revealing their occurrence about 2% of the time and their predominant origin near the quasi-parallel bow shock under typically steadier IMF than usual. This suggests that a stable foreshock and hence foreshock structures or processes may be important in the generation of the majority of magnetosheath dynamic pressure pulses. There was, however, a minority of pulses due to changes in the IMF which could not be explained simply by random events. The dynamic pressure transients (typically around 30 s in duration in the spacecraft frame) are most often dominated by velocity increases along with a small fractional increase in the density, though the velocity is generally only deflected by a few degrees. Since the total pressure is enhanced in these structures, generally by a factor of \( \sim 2 \), they have the potential to impinge upon the magnetopause and have effects within the magnetosphere.

The magnetospheric response to such pressure pulses was addressed in chapter 8, investigating the impacts of the pulses reported in chapter 6 using a comprehensive chain of observations from the magnetopause to the ground. While individual magnetosheath pulses are sharp and impulsive, the response is much smoother with frequencies in the Pc5-6 range being excited in the compressional and poloidal components of the magnetic field. The magnetopause acts like a low pass filter, suppressing timescales shorter than a few minutes, consistent with models of magnetopause motion [Smit, 1968; Freeman et al., 1995; Børve et al., 2011], and further filtering appeared to occur locally within the magnetosphere, perhaps due to the unusual field line resonance frequency profile on this day. Ground magnetometer and radar data along with equivalent ionospheric currents show signatures of travelling convection vortices, similar to the response from pressure variations of solar wind origin. However, the signatures are associated with groups of magnetosheath pulses rather
than individual ones. Thus the scale-dependent magnetospheric response to these transient pressure variations, results in coherent signatures on longer timescales than any individual pulse.

A number of questions remain outstanding about magnetosheath dynamic pressure pulses. While the results of chapter 7 suggest that the pulses’ predominant origin is due to foreshock structures interacting with the shock, no direct evidence of this has been found so far. Hybrid or kinetic simulations could provide insight into the downstream signatures of foreshock structures and how they compare with the typical properties of the dynamic pressure pulses reported in this thesis. Furthermore, multipoint observations immediately upstream and downstream of the quasi-parallel shock may also aid in understanding the physical processes resulting in these pulses. The three-dimensional structure of the pulses and how they move and evolve in the downstream region is also largely unknown. Multi-spacecraft studies of pulses using smaller spacecraft separations, for instance Cluster, THEMIS during its string-of-pearls configuration or the future MMS mission, could provide a better understanding of these topics. Additionally measurements of the scale sizes of magnetospheric responses, both at the boundary and within the magnetosphere, could prove useful in this regard. These are hypothesised to be more local in general than the response to pulses associated with solar wind discontinuities as presented in chapter 8 and by Dmitriev and Suvorova [2012], though there is little observational evidence reported so far.

The work in this thesis has shown that dynamic pressure pulses in Earth’s dayside magnetosheath are an important source of driving dynamics in the magnetosphere. Methods which infer conditions at the magnetopause from measurements of the pristine solar wind currently fail to predict the times and locations of these structures. Thus magnetospheric dynamics directly driven by these pressure pulses are not captured and it is only through simultaneous observations of the magnetosheath driver and magnetospheric response that this has become apparent. Such multipoint observations are vital in understanding transient processes in the magnetosphere, with the current Van Allen Probes and future MMS missions allowing for an unprecedented dataset in regard to in situ observations of Earth’s space environment.
Credits

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Bibliography


A. Coordinate Systems

A number of standard coordinate systems are used in this thesis, which are described here. Apart from the boundary normal and HDZ geomagnetic coordinates, they are all centred on the Earth.

**Geocentric Solar Ecliptic (GSE)**

- $x$: Towards the Sun
- $y$: In the ecliptic plane towards dusk (opposing planetary motion)
- $z$: Parallel to the ecliptic pole

Relative to an inertial frame, the GSE system has a yearly rotation.

**Geocentric Solar Magnetic (GSM)**

- $x$: Towards the Sun
- $y$: Perpendicular to Earth’s magnetic dipole and the Sun-Earth line
- $z$: Component of the Earth’s magnetic dipole perpendicular to the Sun-Earth line

The GSM frame has seasonal and daily variations compared to GSE due to the tilt of the Earth’s axis.

**Boundary Normal (LMN)**

Boundary normal coordinates are defined relative to some boundary. Here the conventions applied to the magnetopause are described.

$L$: Projection of the GSM $z$ axis on the boundary tangent plane.
$M$: Completes the right hand set.

$N$: Normal to the boundary, usually pointing away from the Earth.

**Geomagnetic (MAG)**

$x$: Completes the right handed set

$y$: Perpendicular to the geographic poles $y = D \times S$, where $D$ is the dipole position and $S$ is the Geographic South Pole

$z$: Parallel to the magnetic dipole axis i.e. toward the Geomagnetic North Pole

Geomagnetic coordinates are fixed in the rotating Earth. The geomagnetic latitude $\Lambda$ and longitude $\Phi$ are defined in this system as

\[
\Lambda[^\circ] = 90 - \frac{180}{\pi} \arccos \left( \frac{z}{r} \right) \quad (A.1)
\]

\[
\Phi[^\circ] = \frac{180}{\pi} \text{atan2} \left( y, x \right) \quad (A.2)
\]

**Solar Magnetic (SM)**

$x$: Completes the right handed set

$y$: Perpendicular to the Sun-Earth line towards dusk

$z$: Parallel to the magnetic dipole axis i.e. toward the Geomagnetic North Pole

Magnetic Local Time (MLT) is defined in this system as

\[
\text{MLT}[hrs] = 12 + \frac{12}{\pi} \text{atan2}(y, x) \quad (A.3)
\]

**HDZ Geomagnetic Coordinates**

The geomagnetic HDZ coordinates used in this thesis are commonly applied to ground magnetometer data.

$H$: (nT) Horizontal component toward geomagnetic north
Coordinate Systems

\[ D: \text{(nT)} \text{ Horizontal component toward geomagnetic east} \]

\[ Z: \text{(nT)} \text{ Vertical component pointing down} \]
B. The L-shell Parameter

The L-shell is a parameter used to describe magnetic field lines in the magnetosphere. It describes those lines which cross the magnetic equator at a distance of the L value in Earth radii (R_E). Often a dipole model of the Earth’s magnetic field is used in its calculation and thus the path along a given L-shell can be described as

\[ r = L \cos^2 \Lambda \]  \hspace{1cm} (B.1)

where \( r \) is the radial distance (in R_E) to a point on the field line and \( \Lambda \) is its geomagnetic latitude.

Figure B.1.: Schematic showing L-shells (in R_E) for dipolar magnetic field lines.
C. Clock Angle Correlation

Procedure

The following details the automated clock angle correlation procedure used in chapter 7 to match up ACE observations of the IMF with the magnetic field measured by THEMIS in the magnetosheath. For each THEMIS magnetosheath crossing:

1. The lag times to the bow shock nose for ACE from the OMNI database were looked up and averaged for the entire crossing. If none were available, then the OMNI lag time was interpolated to the centre of the interval. The resulting lag time is denoted by \( t_1 \).

2. The THEMIS magnetometer data was smoothed by a 1 min running average to filter out turbulence and high frequency waves. This data was then interpolated onto the same resolution as ACE i.e. 16 s. The ACE data for the entire magnetosheath crossing, lagged by \( t_1 \) and buffered either side by 60 mins worth of data, was similarly smoothed.

3. The complex exponential of the GSE clock angle \( z = \exp(i\alpha) \), where \( \alpha = \text{atan2}(B_y,B_z) \), was calculated for both the smoothed THEMIS and ACE data yielding \( z_{msh} \) and \( z_{sw} \) respectively. The mean of \( z_{msh} \) was removed from both data sets and these were cross correlated. The lag corresponding to the peak in the real part of the cross correlation function was extracted as \( t_2 \), a better estimate of the overall lag time for the magnetosheath crossing. This was limited to within 30 mins of \( t_1 \).

4. The magnetosheath crossing was split into intervals of 30 min duration, stepped on by 5 mins at a time. For each interval:
   
a) \( z_{msh} \) was calculated and, after subtracting the mean value, a 30 min Hann window applied. \( z_{sw} \) was also calculated for the interval (buffered either side by 40 mins) using a lag of \( t_2 \), with the mean of \( z_{msh} \) also subtracted. This was then cross correlated with the windowed magnetosheath data.
b) All positive peaks in the real part of the cross correlation function were identified (limited to within 20 mins of $t_2$). Of those peaks, only those at least half the height of the tallest were considered.

c) If only one peak remained, then the lag associated with this peak was used. Otherwise, if previous windows had yielded a good (>0.75) correlation coefficient (see item 4d) then the peak closest to the mean of these lag times was chosen. If no previous windows had good correlation coefficients then the peak closest to a lag of $t_2$ was picked. $t_3$ denotes the chosen lag time for each interval.

d) The Hann weighted correlation coefficient of $z_{msh}$ and $z_{sw}$, the latter now lagged by $t_3$, was calculated.

5. All lags $t_3$ from intervals where the correlation coefficient was greater than 0.75 were accepted, with the lags interpolated for all other intervals. For any intervals before the first or after the last accepted lags, the nearest accepted lag was used. If no intervals yielded an accepted lag then all were set to $t_2$. This final set of lags for each interval is denoted $t_4$.

6. The correlation coefficients were recalculated, using the final lags $t_4$, as well as the Hann weighted root mean squared deviation (RMSD) in the clock angles. These lags were accepted if their correlation coefficient >0.75 or RMSD <30°.

Table C.1 shows the results of this procedure for all spacecraft over all magnetosheath crossings, for which only 30% did not produce a good lag. It was found that this percentage showed no strong dependence on $\theta$, $F$, IMF cone angle or ACE’s distance from the Sun-Earth line. In fact these results agree extremely well with the statistical survey of solar wind (measured by WIND) and magnetosheath (measured by Geotail and Interball-Tail) clock angles of Coleman [2005], which found about 30% of data points exhibited perfect draping within ±10°, 70% were within 30° and that the differences were not, in general, well-ordered in any systematic fashion that could be accounted for by hydrodynamic draping.
Table C.1.: Results of clock angle correlation procedure.

<table>
<thead>
<tr>
<th>Corr. Coef.</th>
<th>RMSD</th>
<th>Intervals</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;0.75</td>
<td>&lt;30°</td>
<td>24%</td>
</tr>
<tr>
<td>&gt;0.75</td>
<td>≥30°</td>
<td>1%</td>
</tr>
<tr>
<td>≤0.75</td>
<td>&lt;30°</td>
<td>45%</td>
</tr>
<tr>
<td>≤0.75</td>
<td>≥30°</td>
<td>30%</td>
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</table>
D. Wavelet Analysis

Here a brief introduction to wavelet analysis is given here, whereas Torrence and Compo [1998] provide a more comprehensive discussion. Wavelet analysis decomposes a time series into wave-like oscillations that are localised in both time and frequency. It is therefore similar to Fourier analysis, which is localised in frequency only. In fact it is perhaps closer to the short-time Fourier transform whereby the Fourier transform is performed on a sliding segment of the time series, providing a dynamic spectrum. Such a method, however, imposes a scale into the analysis (the size of the window used) whereas wavelet-analysis is scale independent because each frequency is treated on its own relevant timescale. Therefore, wavelet analysis offers a time-frequency representation of a signal that offers very good time and frequency localisation.

A number of different wavelet functions $\psi(t)$ can be used as a basis, in this thesis the Morlet wavelet is used, shown in Figure D.1, consisting of a plane wave modulated by a Gaussian

$$
\psi(t) = \pi^{-1/4} \exp(i\omega_0 t) \exp\left(-t^2/2\right)
$$

where $\omega_0$ is a parameter called the nondimensional frequency, taken to be 6 here as per Torrence and Compo [1998].

The (continuous) wavelet transform at time $t$ and frequency $f$ of a time series $x(\tau)$ is defined as the convolution of the time series with a scaled and translated version of the wavelet function

$$
W_x(t, f) = s(f)^{-1/2} \int d\tau x(\tau) \psi^*\left[\left(\tau - t\right)/s(f)\right]
$$
The Morlet wavelet function $\psi(t)$ is defined as

$$s(f) = \frac{\omega_0 + \sqrt{2 + \omega_0^2}}{4\pi f} \approx 0.97 f^{-1}$$

and are thus normalised at each frequency to have unit energy. The scaling (by frequency $f$) and translating (to time $t$) of the wavelet function is what gives the localisation of the transform in time-frequency space, where the frequencies are logarithmically spaced. The wavelet transform is (in general) complex thus has a phase and the wavelet power spectrum is defined as $|W_x(t, f)|^2$. While at any given time $t$ the wavelet power spectrum gives a measure of the local spectrum, this can be averaged in time

$$\overline{W^2_x}(f) = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} |W_x(t, f)|^2 \, dt$$

yielding an unbiased and consistent estimation of the true power spectrum of a time series, comparable to the power spectral density.

Due to the localisation of the wavelet function in time and frequency, any given point in a time series has a corresponding cone of influence in time-frequency space, given by the e-folding time of the (scaled) wavelet function. For the Morlet wavelet this is $\pm s(f) \sqrt{2}$ for a given frequency $f$ either side of the desired time. This is a particularly important concept for jumps or discontinuities in time series, whereby power will be enhanced within the cone of influence centred on the jump.
Wavelet Analysis

The wavelet transform at a given frequency can be thought of as a bandpass filter of a time series, with the response function given by the wavelet function. Since the transform is a full representation of the original time series in time-frequency space, it can be used to reconstruct the original time series by summing over all frequencies and scaling appropriately [Torrence and Compo, 1998].

Wavelet analysis can also be used in comparing two time series $x$ and $y$. The wavelet coherence can be computed, in an analogous way to the Fourier method, as a useful measure of how coherent two time series are in time-frequency space and thus how meaningful their phase differences are. This is defined [Torrence and Webster, 1999] as

$$R^2(t, f) = \frac{|\langle s(f)^{-1}W_x(t, f)W^*_y(t, f) \rangle|^2}{\langle s(f)^{-1}|W_x(t, f)|^2 \rangle \langle s(f)^{-1}|W_y(t, f)|^2 \rangle}$$

(D.5)

where angular brackets denote a smoothing in both time and frequency. For the Morlet wavelet, Grinsted et al. [2004] use Gaussian smoothing in time (of the same temporal width as the scaled wavelet function) followed by a moving average in the logarithmically spaced frequencies.