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The connection between the bow shock at Mercury and the interplanetary magnetic field

ERIK SELLBERG
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Abstract

As the solar wind reaches Mercury it interacts with the planet’s magnetic field slowing down, forming a bow shock in front of the planet and diverting the flow around it. Along with the solar wind comes the interplanetary magnetic field, an extension of the sun’s magnetic field. 

The interaction between the bow shock and the interplanetary magnetic field impacts the behaviour of the plasma both up- and downstream of the bow shock. An important factor is the angle between the normal to the bow shock surface and the interplanetary magnetic field, $\theta_{BN}$. The angle can be divided into two categories: quasi-parallel for when $\theta_{BN} < 45^\circ$ and quasi-perpendicular for $\theta_{BN} > 45^\circ$.

It is expected for a quasi-parallel configuration to have stronger fluctuations in both the solar wind upstream of the bow shock and in the magnetosheath downstream caused by reflected particles backstreaming into the solar wind. Quasi-perpendicular configurations are expected to have less fluctuations in both regions due to fewer solar wind particles being reflected back.

In this thesis this connection is investigated at the bow shock at Mercury using magnetic field data from the MESSENGER mission. By looking at the data when the spacecraft travels through the thin bow shock the local $\theta_{BN}$ angle can be calculated. The fluctuation level is then calculated as the standard deviation of the magnetic field in a 30 second period upstream and downstream of the crossing.

The results found are unexpected as the correlation between $\theta_{BN}$ and the fluctuation levels are weaker and more uniformly distributed than expected compared to similar studies conducted at Earth using the Cluster satellites. This is most likely due to the smaller spatial scale of the Hermean system: the structures perpendicular to the interplanetary magnetic field of upstream activity, such as SLAMS, cover a greater proportion of the bow shock than at Earth allowing them to extend over into neighbouring regions of different $\theta_{BN}$ values, giving a more uniform distribution of the fluctuation levels.

Keywords

Mercury bow shock, Bow shock - interplanetary magnetic field interaction, MESSENGER
Sammanfattning

När solvinden når Merkurius växelverkar den med planetens magnetfält och solvinden saktas ned och avledes till att flöda kring planeten. Då solvinden decelereras formas en chock framför planeten, bogchocken. Tillsammans med solvinden kommer det interplanetära magnetfältet, som är en förlängning av solens magnetfält.

Växelverkan mellan bogchocken och det interplanetära magnetfältet påverkar plasmat både upp- och nedströms från bogchocken. En viktig faktor är vinkeln mellan normalen till bogchocken och det interplanetära magnetfältet, \(\theta_{BN}\). Bogchocken kan delas in i två kategorier: kvasi-parallell då \(\theta_{BN} < 45^\circ\) och kvasi-vinkelrät då \(\theta_{BN} > 45^\circ\).

Vid kvasi-parallela förhållanden förväntas starkare fluktuationer i magnetfältet både uppströms i solvinden och nedströms i magnetskiktet, orsakat av reflekerade partiklar som färdas in i den inkommande solvinden. Kvasi-vinkelräta förhållanden förväntas ha mindre fluktuationer då färre partiklar reflekteras.

I den här uppsatsen undersöks kopplingen vid Merkurius bogchock med data från rymdsonden MESSENGER. Genom att använda data då rymdsonden färdas igenom den tunna bogchocken kan det lokala värdet på \(\theta_{BN}\) uträknas. Fluktuationsnivåerna räknas ut som standardavvikelsen av magnetfältet under en 30 sekundersperiod uppströms och nedströms från korsningen.

Resultaten är ej som förväntade då kopplingen mellan \(\theta_{BN}\) och fluktuationsnivån är mycket svagare och jämmt fördelade än förväntat, baserat på resultat från jorden från Cluster-satelliterna. Den mest troliga förklaringen är att Merkurius och dess bogchock är mindre än jordens: de strukturer som är vinkelrätta till det interplanetära magnetfältet hos uppströmsfenomen, t.ex SLIMS, täcker då en större proportion av bogchocken än vid jorden vilket tillåter dem att sträcka sig in i närliggande regioner med annorlunda \(\theta_{BN}\) värden, vilket ger en mer jämn utbredning av fluktuationsnivåerna.

Nyckelord

Merkurius bogchock, Växelverkan bogchock/interplanetära magnetfältet, MESSENGER
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Stockholm, June 2023
Erik Sellberg
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<td>Bow Shock</td>
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<tr>
<td>BSC</td>
<td>Bow Shock Crossing</td>
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<td>FAB</td>
<td>Field Aligned Beam</td>
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<td>FS</td>
<td>Foreshock</td>
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<tr>
<td>IMF</td>
<td>Interplanetary Magnetic Field</td>
</tr>
<tr>
<td>IRFU</td>
<td>Institutet för Rymdfysik Uppsala</td>
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<tr>
<td>MAG</td>
<td>Magnetometer</td>
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<td>MHD</td>
<td>Magnetohydrodynamics</td>
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<td>MP</td>
<td>Magnetopause</td>
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<td>MS</td>
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<td>MSO</td>
<td>Mercury Solar Orbital</td>
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<td>SLAMS</td>
<td>Short Large Amplitude Magnetic Structure</td>
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<td>SW</td>
<td>Solar Wind</td>
</tr>
<tr>
<td>ULF</td>
<td>Ultra Low Frequency (waves)</td>
</tr>
<tr>
<td>UTC</td>
<td>Coordinated Universal Time</td>
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List of Symbols Used

The following symbols will be later used within the body of the thesis.

- $\alpha$  Angle between location of BSC and defined axes, ...................... page 17
- $\eta$  Magnetic diffusivity, ...................................................... page 5
- $\kappa$  Electrical conductivity, ................................................... page 5
- $\mu$  Mean value, ................................................................. page 28
- $\mu_0$  Permeability of free space, ............................................. page 5
- $\omega_g$  Gyro frequency, ......................................................... page 5
- $\omega_S$  Solar angular velocity, ............................................... page 7
- $\Psi$  Arrival angle of Parker spiral, ......................................... page 7
- $\rho_g$  Gyroradius, ................................................................. page 36
- $\sigma$  Standard deviation, ....................................................... page 28
- $B$  Magnetic field, ................................................................. page 5
- $E$  Electric field, ................................................................. page 5
- $F$  Generic force, ................................................................. page 5
- $u$  Plasma velocity, ............................................................... page 5
- $v$  Particle drift velocity, ....................................................... page 5
- $\theta_{BN}$  Angle between IMF and shock normal, ......................... page 9
- $a$  Standoff distance, ............................................................ page 16
- $b$  Flaring parameter, ............................................................ page 16
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List of Symbols Used
Chapter 1

Introduction

Mercury, the smallest of the terrestrial planets, has largely been unexplored in comparison to the rest of the solar system. In 2011 the MErcury Surface, Space ENvironment, GEochemistry and Ranging (MESSENGER) mission arrived and carried out its mission collecting data until it executed a controlled crash into the planets surface in April 2015. The second spacecraft to visit the planet, the first being Mariner 10 with only a brief fly-by, MESSENGER was the first to go into orbit and collect detailed data on the rocky world. Aboard MESSENGER the magnetometer (MAG) instrument collected data about the small planet’s magnetosphere as it orbited [1].
As the solar wind hits a magnetised body, such as Mercury, the magnetic field of the object brakes the incoming supersonic solar wind abruptly and forms a shock. At the bow shock, the magnetic field of Mercury acts with the solar wind and the interplanetary magnetic field, an extension of the sun’s magnetic field carried out into space by the particles of the solar wind. The angle between the interplanetary magnetic field (IMF) and the normal of the bow shock, called $\theta_{BN}$, significantly impacts the behaviour of the plasma both up- and downstream of the bow shock region. The angle $\theta_{BN}$ is divided into two states, quasi-parallel ($\theta_{BN} < 45^\circ$), when the magnetic field of the IMF is close to parallel with the bow shock normal, and quasi-perpendicular ($\theta_{BN} > 45^\circ$), when it is closer to perpendicular to the IMF.

This project aims to use the magnetic field data to study statistical distribution of the angle between the interplanetary magnetic field and the normal to the bow shock across the bow shock of Mercury, and it’s effect on the up- and downstream plasma. It is hypothesised that a quasi-parallel configuration will be related to the presence of more non-linear structures upstream, based on results from Earth’s bow shock.

The study is conducted using data from the magnetometer instrument aboard the MESSENGER mission to Mercury which have been analysed using MATLAB. A major tool used in the project for plotting and visually inspecting the MESSENGER data has been the IRFU MATLAB routines.
1.1 Structure of the Thesis

Chapter 2 is a more detailed background on the topic of plasma- and space physics, as well as details of the MESSENGER mission itself. Following this in Chapter 3 the methods used are explained. The results of the study are presented in Chapter 4 along with selected examples of the data. In chapter 5 the results are discussed and compared to similar studies conducted at both Earth and Mercury. Finally chapter 6 summarises and presents suggestions for future work.
Chapter 2
Background

This project lies within the field of space physics; a field dedicated to researching the physics of our sun, the solar wind and how it affects the celestial bodies within the solar system. In space physics in-situ observations are used, that is data collected on location by probes and spacecraft. The following chapter is an introduction to the key concepts discussed in this thesis, starting with a general background of space and plasma physics and a more detailed description of the areas relating to this thesis.

2.1 General Introduction

2.1.1 Space Plasmas

Plasma is a state of matter in which a gas is partially or fully ionised, meaning that the particle is charged by losing or gaining an electron. The majority of the ordinary matter in the universe is in a plasma state, including stars and interstellar matter. The plasmas that will be discussed in this thesis are extremely thin, with a density low enough to assume that there are no kinetic collisions between particles, and they only interact through electromagnetic fields as they move. Space plasmas consist mostly of protons and electrons, but can also include heavier molecules in areas such as ionospheres. The plasma is considered homogeneous: it is assumed that the amount of positively charged particles to be equal to the amount of negatively charged ones. This allows for the assumption of quasi-neutrality, meaning that on average the plasma is neutral [3].

As the charged particles move due to the electromagnetic fields they generate new/modify the existing electromagnetic fields as they move, creating
constantly changing intricate interactions and movement within the plasma. Each particle affects all others (even over long distances), thus the plasma exhibits a collective behaviour. It is possible to model the plasma as an electrically conductive fluid, a theory called magnetohydrodynamics (MHD), which uses Maxwell’s equations for electromagnetism together with differential equations for fluid dynamics (continuity and conservation of mass) to model the plasma [4] [3]. For the scope of this thesis, it is not required to formulate the governing equations but only to understand the basics.

In ideal MHD it is assumed that the conductivity in the fluid is large enough to use the ideal version of Ohm’s law, which states that \( \mathbf{E} + \mathbf{u} \times \mathbf{B} = 0 \), meaning that in a stationary plasma the electric field is \( \mathbf{E} = 0 \) and in the presence of an electric field \( \mathbf{E} \neq 0 \) the plasma must flow with a velocity \( \mathbf{u} \neq 0 \). A consequence of ideal Ohm’s law being applicable is that the magnetic flux through a given surface will be constant. This means that the magnetic field lines move with the particles of the plasma, that they’re “frozen-in” the plasma, following it as it flows. This ideal version generally holds for high magnetic Reynold’s numbers (\( Re_m \), eq. 2.1) and breaks down at low numbers which usually involves small length scales, allowing for magnetic reconnection. In eq. 2.1 \( \mathbf{u} \) is the plasma velocity, \( L \) is the characteristic length and \( \eta \) is magnetic diffusivity, defined as the inverse of the permeability of free space times the materials electrical conductivity [3].

\[
Re_m = \frac{uL}{\eta}, \quad \eta = \frac{1}{\mu_0 \kappa}
\]  

Moving on from plasma as a whole, to get a simple understanding of movement in plasma consider a single charged particle (ion or electron). The charged particle acted on by electric- and magnetic fields \( \mathbf{E} \) and \( \mathbf{B} \) respectively, it experiences the Lorentz force. Together with Maxwell’s equations for electromagnetism, it is possible to derive the equations for the motion of a charged particle under the effect of different electric and magnetic fields. Following are the most common concepts [4]:

- Gyration, \( \omega_g = \frac{qB}{m} \): A particle of charge \( q \) and mass \( m \) will gyrate around a guiding magnetic field line, as seen in figure 2.1a, with gyro frequency \( \omega_g \).

- \( \mathbf{E} \times \mathbf{B} \) drift, \( \mathbf{v}_E = \frac{\mathbf{E} \times \mathbf{B}}{B^2} \): In the presence of both electric and magnetic fields, both negative and positive particles will drift in the same direction but gyrate in opposite directions around the field line, as seen in figure 2.1b.
Drift, $\mathbf{v}_F = \frac{\mathbf{F} \times \mathbf{B}}{q\mathbf{B}^2}$. For any generic force $F$ that is able to change the acceleration of the particle will give rise to a drift velocity perpendicular to both the magnetic field and the applied force. This results in drift as seen in figure 2.1c. More specifically, this effect can also occur if there exist a gradient in the magnetic field, as one side of the gyration orbit will be stronger than the other, a drift in the direction of the gradient. Negative and positive particles drift in different directions for both cases.

Magnetic mirror: In converging magnetic fields particles will gradually convert its perpendicular energy to parallel, resulting in less ”forward” movement until a mirror point is reached where the particle will bounce, as seen in figure 2.1d

2.1.2 The Sun and the Solar Wind

Making up over 99% of the mass of the solar system with a radius of 695 000 km the sun consists of about 90% hydrogen and 10% helium with trace amounts of heavier elements. Due to the extreme temperature from the fusion in the sun the majority of the gases are in an ionised state. The surface of the sun is called the photosphere, a thin surface where most of the light reaching Earth originates from. Above it the density of the plasma exponentially decreases in the sun’s atmosphere consisting of the chromosphere and corona. The chromosphere is a shallow, cool region that is followed by a transition
region into the corona. The corona is a very hot, extremely diffuse region that stretches far from the sun into interplanetary space for millions of kilometres. Due to the extreme pressure difference between the corona and interplanetary space a continuous stream of plasma flows outwards into the solar system despite the sun’s gravity. This plasma, called the solar wind, mostly consists of electrons and protons with some heavier ions such as alpha particles. The solar wind carries with it and extends the solar magnetic field throughout the interplanetary medium, the field lines of the solar magnetic field being attached to the charged particles in the solar wind due to the frozen-in-flux theorem. This extended solar magnetic field is referred to as the interplanetary magnetic field \([3]\).

The solar wind travels radially out from the sun, but due to the rotation of the sun the magnetic field carried along becomes twisted in a spiral shape called the Parker spiral. This causes it to arrive at an angle, increasing with increasing distance from the sun, which can impact the direction of the IMF at the location. The arrival angle can be calculated with the following equation \([5]\):

\[
\Psi = \arctan \left( \frac{\omega_S r}{u_{SW}} \right)
\]  

(2.2)

With a solar angular velocity of \(\omega_S = 2\pi/25 \text{ days} = 2.9 \cdot 10^{-6} \text{ rad/s}\) the results for Earth are with local solar wind speed \(u_{SW} = 320 \text{ km/s}\) and orbital distance \(r_E = 1 \text{ AU}\) an angle of \(\Psi_E = 53^\circ\). For Mercury, with local solar wind speed \(u_{SW} = 430 \text{ km/s}\) and distance \(r_M = 0.387 \text{ AU}\) gives an angle of \(\Psi_M = 22^\circ\) \([6]\).

2.1.3 Collisionless Shocks

In order to understand the shocks that exist in rarefied space plasma, let’s first briefly look at conventional shock waves. Consider an object travelling along a straight path through a gas. In subsonic flow particles ahead (upstream) of the object are “warned” of its arrival, since the particles displaced by the moving object will in turn displace the particle in front of them, thus transferring information upstream allowing particles to move before the object arrives. The speed at which the particles, and thus information, travel at is the speed of sound in the medium. If the object instead travels faster than the speed of sound the particles cannot travel ahead and instead pile up ahead of the object and become compressed, forming a shock wave. A shock wave slows down the incoming supersonic flow, the speed behind it (downstream) becoming
subsonic. This drastic change is, unlike the sound waves in subsonic flow, not adiabatic, meaning that shock waves change the properties of the gas they passing through by compressing and heating it \footnote{3}.

For space plasma the density is low enough that shocks due to collisions occur infrequently enough to be ignored. However, instead of dissipation and compression occurring due to collisions it instead is due to the interaction of magnetic fields on the charged particles in the plasma (particle-wave interaction). This gives rise to shock waves in rarefied space plasma similar to ones that can be observed on Earth, for example with supersonic aircraft \footnote{3}.

For standing shocks, such as the bow shock forming in front of objects in a supersonic flow, it is convenient to use a shock frame of reference for calculations. This means that the observer travels with the shock while the incoming flow travels at supersonic speed.

\subsection*{2.1.4 Mercury and the Hermean System}

The innermost planet, Mercury is a small terrestrial world with a mean orbital radius of 0.387 AU and mean planetary radius \( R_M = 2440 \text{ km} \). Mercury’s rocky surface is heavily cratered and temperatures fluctuate heavily between day and night side due to the proximity to the sun and lack of atmosphere. The planet’s composition is unusual as the ratio of silicates to metals is high giving a higher than expected density. Mercury’s magnetic field is thought to arise from a hydrodynamic dynamo which induces a magnetic field by movement of electrically conductive liquids in the planets core, most likely caused by convection of molten iron from the planets creation. However, the field is much weaker than predicted and the reason why is not certain. Some theories include a partially solidified core which causes a weakened field, or a negative feedback loop from the magnetosphere weakening it \footnote{7}.

Regardless of the magnetic field’s origin, the MESSENGER mission accurately measured it. With a magnetic field strength of approximately \( 195 \pm 10 \cdot R_M^3 \text{ nT} \) it has approximately 1% the strength of Earth’s magnetic field. It is southward directed and tilted by 3° from the planet’s axis of rotation. Unlike Earth the field is internally displaced northward at about 0.16 \( R_M \), giving the north and south pole different magnetic properties, for example the surface field strength at the north pole is 3.4 times greater than at the south \footnote{7} \footnote{6}.

As at Earth, when the solar wind reaches Mercury’s magnetosphere it slows down to sub-magnetosonic speeds and deflects around the magnetosphere as a standing shock wave forms in front of the planet. This shock wave
is called the bow shock and takes the form of a paraboloid, creating a boundary between the Hermean system and the solar wind. A diagram illustrating this can be seen in figure 1.1. The shape and distance from the planet depends mostly on solar wind properties such as speed and density, but also on the angle of the incoming IMF [8]. An important parameter related to the bow shock in this thesis is the shock normal, $N$, which is defined as the vector normal to the shock surface. As the IMF reaches the bow shock it forms an angle to the local shock normal, denoted as $\theta_{BN}$. Depending on $\theta_{BN}$ the shock is classified into two categories: quasi-perpendicular for $\theta_{BN} > 45^\circ$ and quasi-parallel for $\theta_{BN} < 45^\circ$ [9]. At any given time, the local value of $\theta_{BN}$ can be different at different parts of the bow shock. This can be seen in figure 2.2 where the blue and red parts of the bow shock represents the local values.

Directly downstream of the bow shock lies the magnetosheath (MS), stretching from the bow shock to the magnetopause, a transition region between the bow shock and the magnetosphere. As the solar wind encounters and interacts with the magnetosphere it is decelerated at the bow shock and deflects around the magnetosphere changing the flow direction of the solar wind. At both Earth and Mercury, on average the region has a greater magnetic field strength and plasma density compared to upstream solar wind values [10] [3]. Generally it is a turbulent (meaning high fluctuation in ion flux and magnetic field strength), anisotropic region containing high temperature plasma. Rich in phenomena such as different modes of waves and particle beams, it is complicated to study in detail [11].

At Earth both upstream and downstream regions exhibit different levels of activity and turbulence depending on the local $\theta_{BN}$ and solar wind properties [12] [10]. In the following sections both cases effect on the upstream solar wind and downstream magnetosheath regions are explored further.

## 2.2 Shock Structure

### 2.2.1 Quasi-Parallel Shocks and Structures

A quasi-parallel configuration gives rise to a generally more complex environment due to the shock being a spatially extended and inhomogeneous region that contains small length scale objects that continuously reform within it. From studies of the Earth’s magnetosphere it is expected to find a large foreshock upstream of the bow shock in this geometry, consisting of reflected backstreaming ions propagating sunwards in the frame of the bow shock. As these ions travel upstream they can be classified into two different populations:
reflected and diffused. Reflected ions represent an anisotropic ion beam, called a Field Aligned Beam (FAB), that is focused parallel to the magnetic field lines and travel sunwards from the bow shock. Diffuse ions represent a much larger fraction of the total foreshock ions, populate an isotropic 3D-shell and travel at lower velocities \([13]\). Interacting with the incoming solar wind these populations form upstream structures \([14]\) \([15]\). This includes ultra low frequency (ULF) waves that are associated with the diffuse population of ions in the foreshock. Caused by the backstreaming ions that destabilise the incoming solar wind plasma, these waves travel anti-sunwards in the frame of the solar shock, whilst the backstreaming ions travel sunwards. As they reach and interact with the energetic ions of the bow shock, amplitudes rapidly grow and form SLAMS \([12]\) (Short Large Amplitude Magnetic Structures), which are localised increases in magnetic field strength. The shock transition itself is made up by a patchwork of these magnetic structures, SLAMS. As they reach the shock they compress and replace earlier magnetic structures that pass on downstream into the magnetosheath: a cyclic reformation of the quasi-parallel shock \([9]\).

Downstream of the quasi-parallel shock the magnetosheath is generally more turbulent compared to downstream of quasi-perpendicular shock \([10]\). Here, the local structure is heavily influenced by the upstream condition; the SLAMS from the foreshock continue past the bow shock and into the magnetosheath \([16]\), and intensive fluctuations in density and magnetic field strength have also been observed \([11]\). Transient areas of increased density and velocity are observed in the quasi-parallel magnetosheath, called magnetosheath jets. At Earth they’re found approximately 10 times more often at quasi-parallel geometries and are more strongly turbulent compared to quasi-perpendicular, suggesting a correlation between \(\theta_{BN}\) and the jets. These jets travel through to the magnetosphere, where they have been connected to several phenomena such as magnetospheric compression, a brighter auroral display and the generation of sub-storms \([17]\).
Figure 2.2: Diagram of the basic structure of the bow shock and foreshock at Earth for different IMF angles, at 0°, 45° and 90° respectively. Here the foreshock regions are shown, where it is expected to find greater upstream disturbances in the solar wind. Source: [18] (Reprinted under Creative Commons License)

2.2.2 Quasi-Perpendicular Shocks and Structures

In general quasi-perpendicular oriented shocks are calmer and less turbulent, and have a cleaner appearance in data. This is partly due to particles being confined close to the shock by their perpendicular gyromotion around the magnetic field lines. In other words, since the magnetic field lines are perpendicular to the bow shock, there’s little room for the gyrating particles to escape upstream (unlike quasi-parallel, where gyrating particles bounce can bounce back along the field lines). This leads to quasi-perpendicular shocks being much less connected to upstream events such as ULF waves and SLAMS [19], giving rise to fewer upstream disturbances and structures.

For the quasi-perpendicular configuration, the magnetosheath is a less turbulent region. With less upstream activity to pass downstream it has less ion and magnetic field strength fluctuations, on average being around half of the quasi-parallel configuration [11]. As previously stated, magnetosheath jets are much rarer and have lower intensity in this region. However, this does not mean that it is an empty region as it is still home to fluctuations caused a temperature anisotropy \( T_{\text{perp}} \gg T_{\text{par}} \) that can lead to ion cyclotron instability and mirror instability [10]. One example of this is a background fluctuation: it arises due to the fact that a small fraction of the incident ions are reflected. This reflected population will initially travel along their upstream field line, but eventually return to the bow shock where they cross into the magnetosheath. Here they form a ring beam distribution which gyrates...
around the initial population that travelled through without reflection. This non-linear structure gives rise to a background instability, that further on can compete/merge with other phenomena and grow as it moves downstream [16].

### 2.3 The MESSENGER Mission

Launched in 2004, the MESSENGER mission to Mercury was the first proper mission to study the planet. Until its arrival the only in-situ measurements and images came from the fly-by of the Mariner 10 probe, who’s discovery of the Hermean magnetic field raised many questions.

After initial fly-by’s of Mercury the MESSENGER spacecraft was placed in a highly elliptic and highly inclined orbit allowing for it to travel through different regions of the magnetosphere in each orbit. Every orbit thus allowed it to cross through the magnetopause into the magnetosheath and on through the bow shock into interplanetary space and back through the bow shock [1]. For this thesis, data from the two bow shock crossings on each orbit and the data upstream and downstream of it are used.

#### 2.3.1 The MAG instrument

The MESSENGER mission carried a magnetometer instrument in order to collect data on the planet’s magnetic field as it orbited. The instrument is referred to as MAG (the MAGnetometer) and is a boom mounted tri-axial fluxgate magnetometer used to measure both strength and vector of the magnetic field [20].
2.3.2 MSO Coordinate System

The coordinate system in the data from the MESSENGER mission that has been used in this thesis is the MSO system, Mercury Solar Orbital. It is defined as following, with Mercury at the origin: $X_{MSO}$ is positive sunwards from Mercury, $X_{MSO}$ is positive northwards from Mercury and $Y_{MSO}$ completes the right hand system [8]. This report will use the MSO system in all following figures.

2.4 Summary

Plasma is a highly complex state of matter that makes up the majority of our known universe. By making certain simplifications, it can be modelled as an electrically conductive fluid. However, in space the plasma is rarefied to the point that kinetic collisions no longer govern the movement, but the interactions between the charged particles that make up the plasma and electromagnetic fields.

As the supersonic solar wind, carrying the IMF with it, hits an obstacle such as a magnetised body it will abruptly slow down creating a standing shock wave in front of the object: a bow shock. How the plasma behaves both up- and downstream of the bow shock will largely depend on the angle of the IMF to the normal of the bow shock, an angle called $\theta_{BN}$. Generally, at Earth’s bow shock, a quasi-perpendicular shock ($\theta_{BN} < 45^\circ$) will result in a more active and turbulent region, with a foreshock consisting of reflected solar wind particles and phenomena such as SLAMS and ULF waves. In a quasi-perpendicular ($\theta_{BN} > 45^\circ$) environment it is generally calmer, less turbulent and less upstream events such as SLAMS and ULF waves.

This thesis uses data from the MESSENGER mission to Mercury, where detailed data on the planet’s magnetic field was captured.
Chapter 3

Methods

3.1 The MESSENGER Data

The data used in this thesis are from two sources. First, the magnetometer data from the MESSENGER mission (MESS-E/V/H/SW-MAG-3-CDR-CALIBRATED-V1.0, public domain dataset) [21]. It consists of magnetic field strength and position for $X$, $Y$, $Z$ components and the absolute value in the MSO coordinate system. The MAG is capable of sampling at a maximum 20 times per second [20]. However, not all data is sampled at this frequency. For ease of execution only data sampled in the maximum $1/20$ s has been used in this thesis.

The MESSENGER MAG data was used in conjunction with a list compiled by Philpot et al. [22] of all bow shock and magnetopause crossings during the MESSENGER mission, which contains information on the boundary it crosses along with the time during the day it occurs and the spacecraft’s position in MSO around Mercury.

3.2 Model of the Bow Shock

The Hermean bow shock needed to be modelled in order to be able to determine the distribution of the shock structure around the planet. The bow shock takes the shape of a paraboloid as the solar wind is compressed and deflected by Mercury. For this thesis, it was modelled with a method as described by Merka et al. in [23]. The paraboloid used in the model is given by eq. 3.1.

$$X_{MSO} = a - b(Y_{MSO}^2 + Z_{MSO}^2)$$  \hspace{1cm} (3.1)
Where $X_{MSO}, Y_{MSO}, Z_{MSO}$ are positional coordinates in the MSO system where the solar wind flows in the negative $X_{MSO}$ direction, $a$ the standoff distance (distance from the planets centre to the bow shock) and $b$ the flaring parameter. Since the model was developed for Earth, it does not translate directly to Mercury and $b$ was instead determined by choosing a value that fit observations according to the model used by Winslow et al. [8]. The best fit value was empirically determined to $b = 0.18$ by plotting a line of best fit through the location of all bow shock crossings used, as can be seen in figure 3.1.

Figure 3.1: Each red dot represents a BSC and the black line the average bow shock crossing shape. Here $\rho_{MSO}$ is defined as $\rho_{MSO} = \sqrt{Y_{MSO}^2 + Z_{MSO}^2}$. Both axes are in terms of Mercury radii, $R_M$. Note that in this figure the black line is an average bow shock, and each crossing has it’s own bow shock model with different $a$ values.

With the flaring parameter decided and the position of the spacecraft known for each specific bow shock crossing (BSC), it is possible to solve for $a$, which determines the shape of the paraboloid for each crossing event. In eq. 3.2 the coordinates of the bow shock event are used and are denoted as $X_{BSC}, Y_{BSC}$ and $Z_{BSC}$ respectively. When calculating the individual $a$ values
some crossings had standoff distances that are extreme, being either below the planets surface \((a < 1 \cdot R_M)\) or very distant \((a > 5 \cdot R_M)\). These extreme values make up 18% of the total eligible bow shock crossings and are most likely the result of unusual high or low solar wind parameters, and have been excluded from the data used in the results.

\[
a = Z_{BSC} + b(Y_{BSC}^2 + Z_{BSC}^2)
\] (3.2)

This equation 3.2 can also be rewritten in order to plot the bow shock in different planes: \(X_{MSO}Y_{MSO}\), \(X_{MSO}Z_{MSO}\), \(Y_{MSO}Z_{MSO}\) and \(X_{MSO}\hat{B}_{IMF}\) respectively. The plane \(X_{MSO}\hat{B}_{IMF}\) is defined as a plane spanned by the \(X_{MSO}\) vector and the unit vector \(\hat{B}_{IMF}\) which is the direction of the IMF for that specific crossing. Thus the direction of this plane changes with each crossing.

For the plane \(X_{MSO}Y_{MSO}\) (eq. 3.3) the z-position is fixed and the x-position is plotted as a function of the y-position. For \(X_{MSO}Z_{MSO}\) (eq. 3.4) the y-position is fixed and x-position is plotted as a function of z-position. For \(Y_{MSO}Z_{MSO}\) (eq. 3.5) with a fixed x-position, the equation needs rewriting as it will now instead take the form of a circle (the bow shock parabola viewed from the front). For \(X_{MSO}\hat{B}_{IMF}\) it is plotted individually for each crossing with only the \(X_{MSO}\) axis remaining constant for all crossings.

\[
X = a - b(Y^2 + Z_{BSC}^2)
\] (3.3)

\[
X = a - b(Y_{BSC}^2 + Z^2)
\] (3.4)

\[
Y = \pm \sqrt{\frac{(a - X_{BSC})}{b} - Z^2} \rightarrow Y^2 + Z^2 = \sqrt{\frac{(a - X_{BSC})}{b}}
\] (3.5)

An example of a bow shock crossing plotted with this method can be seen in figure 3.2. The blue line represents the individually plotted bow shock for the bow shock crossing, the red vector in the shock normal and yellow vector the direction of the IMF. Magnitude of the vectors are not to scale.
3.2.1 Denoting Position Along the Bow Shock

In order to convey the position along the bow shock where the crossing is located, the angle from the $X_{MSO}$-axis to the BSC in all four planes as described in the previous section 3.2 was calculated. This angle, $\alpha$, is defined as $\pm 180^\circ$ from the $X_{MSO}$-axis ($Y_{MSO}$-axis in the $Y_{MSO}Z_{MSO}$ case), with positive and negative definitions for each plane according to figure 3.3.
Figure 3.3: Definition of the angle $\alpha$ for the four planes. The centre of Mercury is at the origin in all four cases.

3.2.2 Calculating the Bow Shock Normal

The normal to the bow shock surface, $\hat{N}$, is required to calculate the angle $\theta_{BN}$. The normal of a surface can be found by taking the gradient of the function describing it, in this case eq. 3.1. The gradient of the function describing the parabola give equation 3.6, which is then normalised in eq. 3.7 giving the shock normal vector for each crossing.

\[
\mathbf{N} = \nabla (X_{BSC} + b(Y_{BSC}^2 + Z_{BSC}^2)) = (1, 2bY_{BSC}, 2bZ_{BSC}) \quad (3.6)
\]

\[
\hat{\mathbf{N}} = \frac{\mathbf{N}}{|\mathbf{N}|} \quad (3.7)
\]

3.3 Bow Shock Crossing Geometry

In the list of crossings [22] the boundary crossed by the spacecraft is denoted by a number from 1-8, as seen in 3.4. Crossings 3 to 6 denotes when the spacecraft crosses the magnetopause (MP) and will not be used in this analysis. Crossings 1 and 2 refers to a bow shock crossing where the spacecraft exits the solar wind and enters the magnetosheath. Similarly, crossing 7 and 8 refers to a BSC in the opposite direction.

The pairs 1, 2 and 7, 8 refers to a single BSC each, with each number
denoting an exit/entrance from the crossing. Thus the data from each crossing has been split into two parts, SW and MS, in order to denote the data from the solar wind and data from the magnetosheath. All further analysis of magnetosheath data is thus from 2 and 7 while solar wind is from 1 and 8.

![Diagram of the solar wind and magnetosheath regions with crossings labeled 1, 2, 3, 4, 5, 6, 7, and 8]

**Figure 3.4:** The definition of the different crossings: 1, 2 and 7, 8 are bow shock crossings while 3 to 6 are magnetopause crossings.

### 3.3.1 Calculating Shock Angle

In order to find the angle $\theta_{BN}$, the angle of the upstream magnetic field to the shock normal must be found. In the data compiled by Philpot et al. [22], the time that each bow shock crossing occurs at is available. The value of the upstream IMF is taken as an average of the 30 seconds before 1, 2 boundary crossings start and after 7, 8 crossings exit into the solar wind. The average is taken separately for each component of the magnetic field, giving the direction before the shock crossing. The angle is then simply found by the following relation:

$$\theta_{BN} = \arccos \left( \frac{B_{IMF} \cdot \hat{N}}{|B_{IMF}| |\hat{N}|} \right)$$

(3.8)
3.4 Statistical Analysis

For the statistical analysis a time period of 30 seconds was also used for the calculations. Longer timescales of up to 5 minutes were also tested, but as more of the upstream/downstream values were included the standard deviation tended towards the similar values for all values of $\theta_{BN}$, flattening the curve giving no discernible results.

As previously stated the data is divided into two groups: SW (from 2 and 7) and MS (from 1 and 8). From this data, the mean magnetic field strength and standard deviation of all components and the absolute value where calculated separately and plotted.

3.5 Visual Inspection

For plotting the magnetic field data a MATLAB routine provided by IRFU (Institutet för Rymdfysik Uppsala) was used. It can be accessed at: [https://github.com/irfu/irfu-matlab](https://github.com/irfu/irfu-matlab).

An example of a plot by this routine can be seen in figure 3.5, which shows the magnetic field over a day. On the x-axis the magnetic field strength in nT, component-wise in the upper graph and the absolute value in the lower. On the y-axis is time, from 00:00:00 to 24:00:00. Time is given in UTC.
Figure 3.5: The magnetic field strength on 1/4/2011 plotted by the IRFU MATLAB routines: individual components in the top graph, absolute value on the bottom. The x-axis is in nT and y-axis time of day from 00:00 to 24:00.
Chapter 4

Results

In the following section the major results of the study will be presented, the statistical analysis as well as some typical examples of bow shock crossings for different shock geometries.

4.1 Typical Examples

In this section typical examples of bow shock crossings are presented and how they appear in the data, along with plots of typical quasi-perpendicular and quasi-parallel bow shock crossings are presented.

First, an example of a typical bow shock crossing is presented. In figure 4.1 the spacecraft crosses through the bow shock several times in quick succession starting at 13:35 where it initially enters denoted by the sudden increase in magnetic field strength. Since the bow shock fluctuates and moves, the spacecraft enters/exit through the thin shock rapidly, settling inside the magnetosheath at around 13:52. Keep in mind that this is a zoomed-in view in both time and magnetic field strength (nT), so in coming examples focusing on the solar wind or magnetosheath the shock itself will not be as clear.
Figure 4.1: Example of how typical bow shock crossings are expressed in magnetic field data. The first dashed line marks the entrance into the bow shock, crosses in and out and finally exits into the magnetosheath at the second line. The definition by Philpot et al. [22] is that the spacecraft is inside the bow shock between the lines.

A typical quasi-perpendicular crossing can be seen in figure 4.2. This example is of geometry 1 to 2 meaning that it exits the solar wind and enter the magnetosheath with the solid line marking boundary 1 (entrance) and the striped line boundary 2 (exit). In this graph is plotted with 30 minutes before and after the crossing event.

As described in Chapter 2 the quasi-perpendicular crossing is expected to have much less turbulence both upstream and downstream. The activity upstream in the solar wind is indeed typically low as expected with very low variance in the overall strength of the magnetic field with a standard deviation in the absolute value of $\sigma(B) = 1.5$ nT in the solar wind. The turbulence increases as the spacecraft crosses the boundary into the magnetosheath to $\sigma(B) = 4.5$ nT in the absolute value.
Figure 4.2: Example of typical quasi-perpendicular bow shock crossing. This particular example occurred 2012-3-27 at 11:20 UTC with an angle of $\theta_{BN} = 82^\circ$. The standard deviation (absolute value) is $\sigma(B) = 1.5 \, nT$ in the solar wind and $\sigma(B) = 4.5 \, nT$ in the magnetosheath.

In figure 4.3 a typical crossing of a quasi-parallel shock is instead plotted. Again the crossing is of boundaries 1 to 2, with the solid line marking boundary 1 (entrance) and the striped line boundary 2 (exit) plotted 30 minutes before and after the crossing.
Here it is clear that the upstream solar wind is much more turbulent as expected in all three components, increasing as the spacecraft nears the bow shock. The standard deviation is now $\sigma(B) = 8.1$ nT in the solar wind. After the shock in the magnetosheath the turbulence is as expected greater with a $\sigma(B) = 15$ nT.

### 4.2 Distribution

The first part of the thesis was to study the distribution of crossings along the bow shock and their respective shock angle $\theta_{BN}$. First, a histogram of the total amount of crossings is shown in figure 4.4. The total amount of crossings is 1633 (i.e 1633 pairs of 1, 2 and 7, 8 geometries).

The distribution is heavily skewed toward the upper end, with a majority of the crossings being quasi-perpendicular. For a random direction of an ideal IMF with parallel field lines, only one point along the bow shock’s surface will be exactly $\theta_{BN} = 0^\circ$. As the IMF comes in contact with the bow shock further outward from this point, the local $\theta_{BN}$ value increases and so will the area in which this angle is occurring. For example, if the IMF is purely radial, that $\theta_{BN} = 0^\circ$ on the nose of the bow shock, that will be the one point
where $\theta_{BN} = 0^\circ$. Radially outward along the surface of the bow shock, the distribution should follow the sine of the angle $\theta_{BN}$, so that the number of crossings is proportional to $\sin(\theta_{BN})$. This is amplified by, as explained in section 2.1.2, that the Parker spiral is more radial at Mercury making this distribution more likely. While the results are not exactly proportional to $\sin(\theta_{BN})$, the general form matches. Note that in reality the bow shock is not a perfect surface and will vary locally as will the magnetic field lines of the IMF.

![Figure 4.4: The distribution of the angle $\theta_{BN}$ for all BSC:s used in this thesis. The total count is 1633.](image)

Furthermore using the definitions of the angle $\alpha$, as described in section 3.2.1, the angle of at each bow shock crossing is plotted against the position along the bow shock in figure 4.5. This is done for $X_{MSO}Y_{MSO}$, $X_{MSO}Z_{MSO}$, $Y_{MSO}Z_{MSO}$ and $X_{MSO}\hat{B}_{IMF}$ planes. Each cell represents an interval of $1^\circ$ for $\theta_{BN}$ from $1^\circ$ to $90^\circ$ and $4^\circ$ for $\alpha$ ranging from $-180^\circ$ to $180^\circ$. The colourbar next to each plot indicates the amount of crossings in each bin, with the total again being 1668 crossings. The top graphs are plotted using the raw data and the lower graphs have been normalised in the $\alpha$-direction, which means that each horizontal row adds to a total of 1. This allows the colour of each bin to represent the probability of the indicated shock angle $\theta_{BN}$.

Keep in mind that each 2D figure is valid for the entire range of the plots normal value, i.e. in the $X_{MSO}Y_{MSO}$-plane each crossing has individual $z$-values that are not reflected in the data. This leads to effects such as bow
shock crossings appearing to occur behind the planet at $\pm 180^\circ$, when actually they are occurring at the bow shocks flanks far from the planet in the normal direction.

Looking closer at the individual figures some features can be seen. Starting in the $X_{MSO}Y_{MSO}$-plane the distribution is even. In the $X_{MSO}Z_{MSO}$-plane there are two clear values of $\alpha$ with greater densities of crossings. This is most likely due to the shape of the spacecraft’s orbit around Mercury, a highly eccentric ellipse. It is likely that the spacecraft crosses the bow shock at the sunward side of the planet at approximately the same angle, giving the strong lines. The empty area in the $Y_{MSO}Z_{MSO}$-plane is most likely an artefact due to the spacecraft’s eccentric orbit. The empty areas in the $X_{MSO}\hat{B}_{IMF}$ plane is a more interesting result. It shows that at the far flanks behind the planet virtually no quasi-parallel shocks are present, only quasi-perpendicular. This is expected and ties into the distribution of $\theta_{BN}$ as a whole, as it shows that the distant flanks are home to a significant number of quasi-perpendicular shocks even across a variety of IMF directions.

**Figure 4.5:** The shock angle $\theta_{BN}$ plotted against the position angle $\alpha$ for each of the four planes, $X_{MSO}Y_{MSO}$, $X_{MSO}Z_{MSO}$, $Y_{MSO}Z_{MSO}$ and $X_{MSO}\hat{B}_{IMF}$. Each cell represents an interval of $1^\circ$ for $\theta_{BN}$ and $4^\circ$ for $\alpha$. Top graphs are raw data, bottom normalised to show probability.
4.3 Fluctuation Levels

To study the effects of the shock angle on both the solar wind and the magnetosheath, the standard deviation of the magnetic field strength 30 seconds before and after each bow shock crossing was calculated. This data is visualised primarily by using 2D histograms, also called density heatmaps. The mean value ($\mu$) and standard deviation ($\sigma$) was calculated using MATLAB’s built in functions which is defined as eq. 4.1 for a vector $A$ of length $n$:

$$
\mu = \frac{1}{n} \sum_{i=1}^{n} A_i, \quad \sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} |A_i - \mu|^2}
$$

(4.1)

The results were also normalised by the background magnetic field, by dividing each crossing’s standard deviation value by the corresponding magnetic field strength. Finally, histograms of the mean value of the standard deviation were also produced, with bins of 5° range for $\theta_{BN}$ from 0° to 90°. The results are individually presented in their respective following sections.

4.3.1 In the Magnetosheath

For the magnetosheath data the standard deviation is calculated using the 30 sec of background IMF after a crossing of boundary 2 and before boundary 7 (see figure 3.4). First, the standard deviation for each component of the magnetic field plotted against the corresponding shock angle $\theta_{BN}$, with $\sigma$ defined as $\sigma(B) = \sqrt{\sigma_x^2(B) + \sigma_y^2(B) + \sigma_z^2(B)}$.

The colour of each bin represent the amount of crossings within those parameters, with intensity denoted by the corresponding colourbar. Each bin represents 1° in $\theta_{BN}$ and 1 nT in $\sigma$.

The first results plots the raw data in figure 4.6. The second in figure 4.7 plots the value normalised by the background magnetic field. Note that both plots contain a few values above the y-limit present in these figures. It was chosen to limit the y-axis since the few outlying values compressed the majority of values close to the x-axis, thus limiting readability of the figure. See appendix A for the full graphs.

Finally, the mean value of the standard deviation values are plotted in intervals of 5° in figure 4.8. Keep in mind that amount of data in each bin is heavily skewed towards greater $\theta_{BN}$ angles as there are more of them, which
can be seen in figure 4.4.

Figure 4.6: Standard deviation plotted against shock angle in the magnetosheath for $\sigma_x$, $\sigma_y$, $\sigma_z$ and $\sigma = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2}$. Colour represents amount of crossings in cell. Each cell has an interval of $1^\circ$ for $\theta_{BN}$ and $1$ nT for $\sigma$. 
Figure 4.7: Standard deviation normalised by the background magnetic field plotted against shock angle in the magnetosheath for $\sigma_x$, $\sigma_y$, $\sigma_z$ and $\sigma = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2}$. Colour represents amount of crossings in a given cell. Each cell has an interval of $1^\circ$ for $\theta_{BN}$ and 1 nT for $\sigma$.

Figure 4.8: Histogram of mean value of standard deviation for $5^\circ$ intervals of $\theta_{BN}$ in the magnetosheath for $\sigma_x$, $\sigma_y$, $\sigma_z$ and $\sigma = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2}$.

The general form of the components show the similar results, with a heavy
concentration of smaller $\sigma$ values for higher $\theta_{BN}$ values, slightly rising as the $\theta_{BN}$ value decreases in figure 4.6. This is to be expected from previous studies at Earth’s bow shock using data from the Cluster mission such as the results from Karlsson et. al in [24]. However it is much less pronounced than expected in the results from this thesis. Similarly the spread of outlying $\sigma$ values in the entire range of $\theta_{BN}$ is unexpected and hints at much less correlation between $\theta_{BN}$ and indicators of solar wind activity such as $\sigma$.

Looking at figure 4.8 there is a correlation as expected, that the lower values of $\theta_{BN}$ indeed does have a larger $\sigma$ values. Looking component-wise the trend is small, but noticeable and is highly noticeable in absolute value. This does indeed follow the expected results, but to a smaller degree. These results will be discussed more in-depth in the following chapter.

4.3.2 In the Solar Wind

The same data presented for the magnetosheath has also been produced for the solar wind, when the spacecraft is outside the bow shock, i.e 30 seconds before boundary 1 and 30 seconds after boundary 8. First, in figure 4.9, the raw data of standard deviation $\sigma$ plotted against $\theta_{BN}$ for all components of the magnetic field. Second, in figure 4.10, the normalised $\sigma$ values. Last in figure 4.11 are the mean values of $\sigma$ in intervals of 5°. The same weighting of crossings towards higher values of $\theta_{BN}$ as in the solar wind results are present in the magnetosheath too.

As with the magnetosheath results, all results again show weak trends between $\theta_{BN}$ and $\sigma$, especially in figure 4.11 which shows the relation much clearer.
**Figure 4.9:** Standard deviation plotted against shock angle in the solar wind for $\sigma_x$, $\sigma_y$, $\sigma_z$ and $\sigma = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2}$. Colour represents amount of crossings in cell. Each cell has an interval of $1^\circ$ for $\theta_{BN}$ and $1$ nT for $\sigma$.

**Figure 4.10:** Normalised standard deviation plotted against shock angle in the solar wind for $\sigma_x$, $\sigma_y$, $\sigma_z$ and $\sigma = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2}$. Colour represents amount of crossings in cell. Each cell has an interval of $1^\circ$ for $\theta_{BN}$ and $1$ nT for $\sigma$. 
Figure 4.11: Mean value of standard deviation for 5° intervals of $\theta_{BN}$ in the solar wind for $\sigma_x$, $\sigma_y$, $\sigma_z$ and $\sigma = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2}$. 
The expected results of the study were that there would be a stronger connection between the angle $\theta_{BN}$ and the fluctuation levels than was found, as it was expected to find similar results as seen at Earth. An example of how this result was expected to look can be seen in figure 5.1 from the Cluster satellites orbiting Earth. The measurements from Earth shows a factor of approximately 5 in the fluctuations between quasi-parallel and quasi-perpendicular configurations.

In comparison, the results observed in this study at Mercury, figure 4.6 and 4.9 which are presented in a similar way show very little correlation and a much wider spread of values in general. Presenting the data in a different form in figure 4.8 and 4.11 gives a clearer view of a weak relationship with approximately a factor of 2 between quasi-parallel and quasi-perpendicular in the absolute value for the magnetosheath and 1.5 in the solar wind. This gives evidence that, like at Earth, there is a relationship between $\theta_{BN}$ and the fluctuation levels in the magnetic field both in the solar wind and magnetosheath but much weaker.

Looking at other studies of the plasma environment around the Hermean bow shock there are some similar unexpected results regarding the impact of $\theta_{BN}$. A study by Glass et. al [25] found that the distribution of different foreshock populations at Mercury were more uniformly distributed than expected. This uniformity has been attributed to the small spatial scale of the Hermean system and the radial direction of the IMF, due to the smaller arrival angle (see sec. 2.1.2 on the Parker spiral). Furthermore the peak of the diffuse ion population was shifted from the Earth observed expectation of $\theta_{BN} = 10^\circ$ to a higher $\theta_{BN} = 25^\circ$.

A study by Karlsson et. al [26] in which observations of SLAMS at
Mercury are found to be relatively uniformly distributed across the bow shock as well, agrees with Glass et al [25]. It presents results relating to the distribution of $\theta_{BN}$ at the connecting point (where the field line connects to the bow shock) for SLAMS, finding no clear difference across the range of $\theta_{BN}$ ($0^\circ$ to $90^\circ$).

One explanation put forth is that foreshock properties and characteristics connected to the quasi-parallel field bow shock can extend beyond $45^\circ$, up to $\theta_{BN} = 60^\circ$. This is more prevalent during radial IMF conditions, which are expected to occur at Mercury more frequently than at Earth.

The argument of Mercury’s smaller spatial scale is brought up here too, with the bow shock at Mercury being about 20 times smaller than Earth’s. For upstream phenomena that cause increased fluctuations, for example SLAMS, the component perpendicular to the IMF could potentially be a much larger fraction of the bow shock of Mercury compared to the fraction it would be at Earth [26]. Thus, they could stretch over a larger area of the bow shock and into areas with different local $\theta_{BN}$ values. Since the Hermean bow shock is
much smaller, the curvature (and $\theta_{BN}$) will increase at a greater rate than at Earth moving across the surface. Thus, measurements from one bow shock crossing with its own local $\theta_{BN}$ value could contain fluctuation values that originate at field lines of very different $\theta_{BN}$ values. This could explain the uniform $\sigma$ values seen over $\theta_{BN}$ in this study.

An important upstream factor is the gyroradius of the ions in the solar wind. This is the radius of the circle travelled by the particle as it gyrates around a field line, in this case the IMF field lines (see figure 2.1a). The radius is given by the following equation:

$$\rho_g = \frac{v_{perp}}{\omega_g} = \frac{mv_{perp}}{qB} \quad (5.1)$$

Here $v_{perp}$ is the ion velocity perpendicular to the magnetic field and $\omega_g$ is defined in section 2.1.1. Assuming that the energy of the ion is the same (keeping $v_{perp}$ constant), the only difference between Earth and Mercury is the magnetic field strength $B$ of the IMF which at Earth is about 5 nT [5] and at Mercury 30 nT [6]. This gives approximately a factor of 6 difference between the planets at normal solar wind conditions. While significant this is much smaller than the factor of 20 between the size of the bow shocks themselves [26]. This means that as the particles move toward Mercury they have potentially a larger span of $\theta_{BN}$ values in which they can make contact with the bow shock compared to Earth, as the fraction of the bow shock covered by the gyroradius is much greater at Mercury than at Earth.
Chapter 6

Conclusions

This thesis investigates the connection between the interplanetary magnetic field and bow shock at Mercury by measuring the angle between the bow shock normal and the IMF, $\theta_{BN}$. First mapping where along the bow shock the MESSENGER spacecraft crosses through the bow shock, then measuring the fluctuations of the magnetic field both upstream and downstream of the bow shock crossing.

The fluctuations were measured as the standard deviation of the magnetic field 30 seconds before and after the spacecraft crosses the bow shock. The results were unexpected compared to similar results from Earth’s bow shock. The correlation between the angle $\theta_{BN}$ and the fluctuation levels in the magnetic field were weaker than expected and the data was more spread out.

Other studies \cite{26} \cite{25} argue that this can be explained by the smaller spatial scale of the bow shock at Mercury compared to Earth, which is about a factor 20 smaller. This means that any spatial component perpendicular to the IMF field lines will cover a proportionally larger area of the bow shock, and thus larger range of $\theta_{BN}$ values, at Mercury than at Earth. This means that local measurements of magnetic field fluctuations can "bleed over" into other regions with different $\theta_{BN}$ values, giving a more uniform distribution over all. Other arguments also brought up include the fact that properties of the quasi-parallel foreshock is known to extend up to $\theta_{BN} = 60^\circ$ and more prominently radial direction of the IMF at Mercury compared to Earth.
6.1 Future Work

Future work with currently available data (from MESSENGER) could include looking at more markers of upstream/downstream activity than just standard deviation, such as other solar wind properties such as solar wind mach number. Other types of analysis could also be done in regards to what kinds of waves are present in the data and the impact of $\theta_{BN}$ on them, which could be done for example by Fourier analysis of the magnetic field before/after bow shock crossings. Signs of different waves modes can be seen when looking component-wise in figure 4.8 and 4.11, where the fluctuations are much weaker in the x-direction compared to y and z and relate this to the direction of the IMF.

In the future the spacecraft Bepi-Colombo, which completed it’s first fly-by of Mercury during the writing of this thesis, will arrive in Mercury orbit at around 2025 and carries with it more advanced sensors than MESSENGER. This will not only provide more data for similar analysis as done in this thesis, but also from more instruments such as measuring the electric field as well.
References


Appendix A

Results: Complete Graphs

Following appendix shows the same results as chapter 4 but with the y-axis unlimited, showing all results. As the y-axis varies, so does the value in nT bounded by each cell.

Figure IA.1: Standard deviation plotted against shock angle in the magnetosheath. Colour represents amount of crossings in cell. Each cell has an interval of 1° for θBN. This appendix version shows all results.
Figure IA.2: Normalised standard deviation plotted against shock angle in the magnetosheath. Colour represents amount of crossings in cell. Each cell has an interval of $1^\circ$ for $\theta_{BN}$. This appendix version shows all results.

Figure IA.3: Standard deviation plotted against shock angle in the solar wind. Colour represents amount of crossings in cell. Each cell has an interval of $1^\circ$ for $\theta_{BN}$. This appendix version shows all results.
**Figure IA.4:** Normalised standard deviation plotted against shock angle in the solar wind. Colour represents amount of crossings in cell. Each cell has an interval of 1° for $\theta_{BN}$. This appendix version shows all results.