

# **Magnetosheath Jets: From the Bow Shock to the Magnetopause**

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## Abstract

When the supersonic solar wind meets Earth's magnetosphere, a shock wave forms in space. Shocked plasma flows around the edges of the magnetopause in a hot, dense, and turbulent layer called the magnetosheath. Magnetosheath jets are localised pulses of high-dynamic pressure plasma originating at the terrestrial bow shock and propagating Earthward through the magnetosheath. As flows of mass and energy they couple the solar wind and foreshock to the magnetopause and magnetosphere. In this thesis we investigate several aspects of magnetosheath jets using a database of over 13,000 jets observed by the THEMIS spacecraft over 11 years. Using simultaneous measurements of the upstream solar wind, we explore how the solar wind controls jet formation and propagation, finding that jets reach the magnetopause 17x more often during low IMF cone angle solar wind, and 8x more during high solar wind speeds, compared to the opposite condition. We investigate the properties of jets in the magnetosheath, comparing observations near the bow shock and near the magnetopause. We find that jets typically possess higher  $\beta$  than their surroundings at the magnetopause, making jet plasma likely to suppress reconnection according to the  $\Delta\beta$ -shear condition. Despite this, we see that individual jets exhibit sufficient magnetic field fluctuation such that most jets may be able to alter reconnection from what would be expected from the IMF, that is, trigger it during northward IMF and suppress it during southward IMF. Using a rich and complex case study example, we explore the magnetopause response to jet impacts, finding jets to be intrinsically linked to localised bursty reconnection and magnetopause dynamics, while developing analysis tools for application to similar events. The results shown in this thesis represent a significant advancement towards being able to forecast the space weather effects arising from magnetosheath jets.

*Dedicated to the memory of my Grandad, Donald William Wallace Davies.*

# Declaration

I declare that, except where explicitly stated otherwise and referenced, the work presented in this thesis is my own.

— *Adrian LaMoury, London, June 2023*

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# Nomenclature

## Abbreviations

CME Coronal mass ejection

ESA Electrostatic Analyser

FGM Fluxgate Magnetometer

FTE Flux transfer event

GSE Geocentric solar ecliptic coordinate system

GSM Geocentric solar magnetic coordinate system

HFA Hot flow anomaly

HMVA Hybrid minimum variance analysis

HSS High speed stream

IMF Interplanetary magnetic field

IQR Inter-quartile range

L1 Lagrange point 1

MMS Magnetospheric Multiscale

SIR Stream interaction region

SLAMS Short large amplitude magnetic structures

THA-E THEMIS probes A-E

THEMIS Time History of Events and Macroscale Interactions during Substorms

## Physical constants

$\mu_0$  Vacuum permeability.  $\mu_0 = 4\pi \times 10^{-7} \text{ H/m}$

$\varepsilon_0$  Permittivity of free space.  $\varepsilon_0 = 8.85 \times 10^{-12} \text{ m}^{-3} \text{ kg}^{-1} \text{ s}^4 \text{ A}^2$

$c$  Speed of light in a vacuum.  $c = 3.00 \times 10^8 \text{ m s}^{-1}$

## Nomenclature

---

$k_B$  Boltzmann constant.  $k_B = 1.38 \times 10^{-23} \text{ m}^2 \text{ kg s}^{-2} \text{ K}^{-1}$

$m_p$  Proton mass.  $m_p = 1.67 \times 10^{-27} \text{ kg}$

AU Astronomical Unit.  $1 \text{ AU} \sim 150 \times 10^6 \text{ km}$

$R_E$  Earth radius  $1R_E \sim 6,371 \text{ km}$

### Symbols

$\beta$  Plasma beta

$\theta_{Bn}$  Angle between magnetic field and shock normal

$d_i$  Ion inertial length

$M_A$  Alfvén Mach number

$R_X$  Reconnection favourability metric

$t_0$  Time in jet interval of maximum magnetosheath to solar wind dynamic pressure ratio

$V_A$  Alfvén speed

*My essays lying scattered on the floor  
fulfil their needs just by being there.*

---

David Bowie, *Conversation Piece*, 1969

# Chapter 1

## Introduction

If it were not for the existence of Earth's magnetosphere, there would be no beings capable of studying it. Our magnetic bubble shields us from the harshness of space, and is one of the key ingredients in the recipe of life. The magnetosphere and our local star, the Sun, are intrinsically linked and their interactions are governed by magnetic fields. The relative proximity of these environments, along with the advent of space technology, have provided us with a uniquely accessible laboratory to study some of the most fundamental physics. That is, the physics of magnetised plasmas. In this thesis we shall explore the fascinating phenomena of magnetosheath jets — impulsive plasma entities formed directly at the interface of the solar-terrestrial link.

In this introductory, chapter we outline key concepts and background information relevant to the research work presented in this thesis. We start with some aspects of fundamental plasma physics, with a focus on collisionless shocks and magnetic reconnection. We then set these processes in their space plasma contexts with the introduction of Earth's magnetosphere and solar-terrestrial interactions, culminating in an exploration of reconnection at the magnetopause. Following this, we describe the phenomena of magnetosheath jets, which is the main subject of this thesis. We summarise the existing body of jet literature, paying particular attention to relevant studies on jet properties, occurrence, evolution, and magnetospheric effects. Finally,

we draw on the background literature to formulate the research questions to be explored throughout this thesis.

### 1.1 An introduction to space plasmas

The physics of magnetised plasmas is detailed in full rigour in many excellent textbooks such as that of Baumjohann and Treumann (2022). Much of the material in following section is derived from that resource. In the interests of brevity, we shall summarise here only the key points of relevance to the reader for understanding later material.

Plasmas are ubiquitous across the solar system and beyond. Indeed, it is believed that upwards of 99.9% of the visible universe is composed of plasma. Despite this, day-to-day human interaction with plasma is very limited. Often referred to as the fourth state of matter, plasma shares many qualities with a more familiar state, gas. The key difference, is that rather than being composed of neutral atoms and molecules, plasmas are a collection of charged particles — positive ions and negative electrons. Being present in equal numbers, their charges counteract and balance such that the plasma as a whole maintains quasi-neutrality. On localised scales, however, slight imbalances and perturbations create charge separation and enable these hot ionised gases to carry electric currents. These currents, and accompanying electromagnetic fields, enable perhaps the most beguiling feature of plasmas — collective behaviour. By this we mean their ability to act as a bulk population while being almost entirely collisionless. Rather than the thermodynamic particle collisions of a neutral gas, plasma particles communicate through electromagnetic Coulomb collisions and wave-particle interactions.

It can be shown that magnetic fields in most space plasmas are ‘frozen in’. That is to say that we can picture fluid elements as being tied to magnetic field lines, following each other in their evolution. It also means that field lines have identities, each belonging to a particular plasma parcel. A consequence of this is that two initially distinct regions of

plasma, each with their own fields, cannot mix or interpenetrate. It is this feature that gives Earth's magnetosphere its protective quality while immersed in the solar wind.

Mathematical descriptions of plasmas exist at different levels. Due to the multi-scale nature of plasma physics, different approaches can be employed depending on the specific task or phenomena of study, and one needs to be able to flexibly move between them. At a fundamental degree (though above the quantum regime), we can study single particle motion. That is, modelling particle trajectories under the influence external fields. In most space plasma contexts however, we are interested in bulk properties (density, temperature, etc.), for which we need a macroscopic description. This is available from kinetic theory. In this system, plasmas are modelled using distribution functions, which combine knowledge of individual particle behaviour with the ability to resolve bulk characteristics with statistical techniques. Computationally expensive but physically rigorous, these models are best applied at small scales, and are useful to describe non-linear phenomena such as shocks and magnetic reconnection. Computational limitations mean that kinetic theory can rarely be applied at large scales. The most common approach to handling this is the theory of magnetohydrodynamics (MHD). This takes a fluid approach to plasma modelling, treating it as a single-species conducting fluid without considering individual particle behaviour. This very commonly used regime is best applied at large scales, for example in solar wind transients or global magnetospheric modelling. It also has the advantage of being relatively computationally inexpensive, making it ideal for situations where fast output is required, such as in real-time space weather forecasting regimes.

### 1.1.1 Characteristic scales and fundamental physics

In order to understand plasma behaviour in different regions and regimes, it is helpful to parameterise their properties in terms of characteristic scales. One important metric is the plasma  $\beta$ . This dimensionless quantity is defined as the ratio of thermal to

magnetic pressure. It is therefore given by

$$\beta = \frac{P_{\text{therm}}}{P_{\text{mag}}} = \frac{nk_{\text{B}}T}{B^2/2\mu_0}, \quad (1.1)$$

for number density  $n$ , temperature  $T$ , and magnetic field magnitude  $B$ . Note that here we give a general formula, but the  $\beta$  can be calculated separately (or combined) for each particle species, or by components perpendicular or parallel to the magnetic field in anisotropic plasmas. The  $\beta$  is a measure of whether a plasma is thermally or magnetically dominated. For  $\beta \ll 1$ , the plasma dynamics are strongly controlled by the magnetic field, whereas for  $\beta \gg 1$  the plasma's thermal properties have greater influence.

Plasmas are capable of carrying and transmitting a variety of wave modes. One of the simplest and most important of these is the Alfvén wave. This can be pictured as a traditional transverse ‘wave on a string’, where the string in question is a field line and the restoring force is magnetic tension. They propagate with a phase velocity given by

$$V_{\text{A}} = \frac{B}{\sqrt{\mu_0\rho}}, \quad (1.2)$$

for a plasma with mass density  $\rho$ . We call this the Alfvén speed, and it is generally used as a characteristic scale for the propagation of information through a magnetised plasma. It is therefore useful to measure other speeds relative to this. To do so, we define the Alfvén Mach number as

$$M_{\text{A}} = \frac{V}{V_{\text{A}}} = \frac{V\sqrt{\mu_0\rho}}{B}, \quad (1.3)$$

for some flow velocity  $V$ . This is a particularly useful quantity when discussing properties of shocks (see next section). We describe a flow speed with  $M_{\text{A}} > 1$  as super-Alfvénic, while those with  $M_{\text{A}} < 1$  are termed sub-Alfvénic.

Another type of plasma wave is the magnetosonic wave. These are analogous to sound



waves in neutral fluids, and can be reached from MHD principles. They propagate with a speed given by

$$c_{\text{ms}} = \sqrt{c_s^2 + V_A^2} \quad (1.4)$$

where  $c_s$  is the sound speed. This, in turn, is given by

$$c_s = \sqrt{\frac{\gamma n k_B T}{\rho}}, \quad (1.5)$$

for adiabatic index  $\gamma$ . Magnetosonic waves have two modes: fast and slow. These can be thought of as being when magnetic and thermal pressure variations are in and out of phase, respectively. The Mach number corresponding to the magnetosonic speed,  $M_{\text{ms}}$ , is often used in the context of shocks, where  $M_{\text{ms}} > 1$  is required.

We can express length scales in terms of inertial lengths. These can be thought of as the distances over which charged particles decouple from magnetic fields. It can be calculated from the plasma frequency ( $\omega_p$ ) and is given by

$$d_i = c/\omega_p = \sqrt{\frac{c^2 m_p \epsilon_0}{n e^2}}. \quad (1.6)$$

For protons in the solar wind, the ion inertial length is around 100 km, and around 50 km in the magnetosheath.

### 1.1.2 Collisionless shocks

Shocks in fluids are non-linear discontinuities caused by an object immersed in a supersonic flow. As well as a physical boundary layer between upstream and downstream regions, shocks can be thought of as an information boundary. This effectively means that it is not possible for disturbances downstream of the shock to counter-propagate and affect the upstream region. Shocks are ubiquitous in space plasmas. A key difference with those seen on Earth (e.g., driven by a supersonic aeroplane) is that shocks in space plasmas can generally be considered to be collisionless. The shock is therefore formed by the collective behaviour of plasma in accordance with its electromagnetic

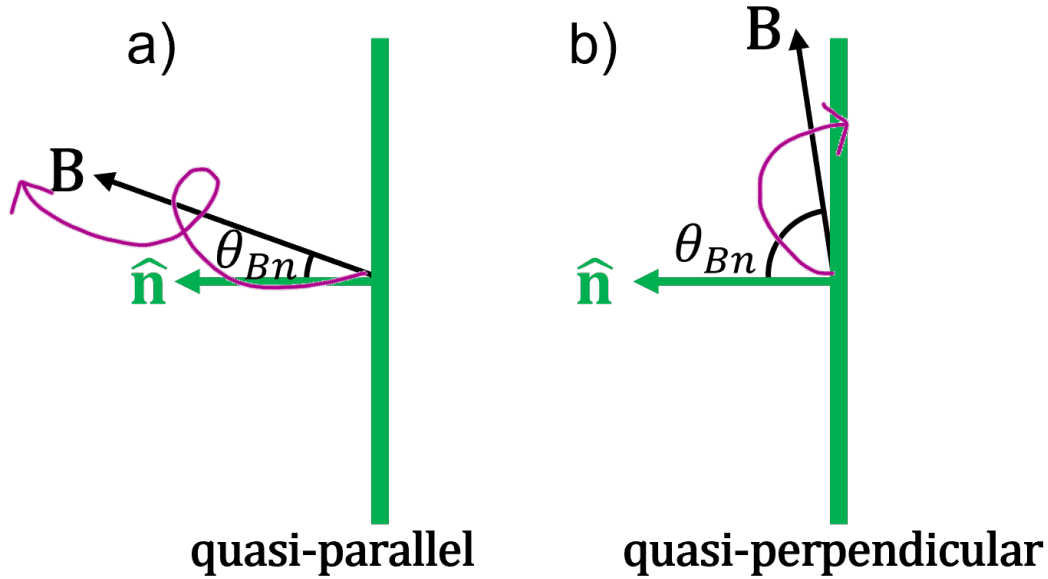
fields. Such a phenomenon is not possible in neutral fluids.

In general, shocks can be considered to slow, compress, and heat plasma flow as kinetic energy is dissipated. The change in properties from upstream to downstream is given by a set of conservation equations known as the Rankine-Hugoniot jump conditions (see, e.g., Burgess and Scholer, 2015):

$$\begin{aligned}
 [\rho V_n] &= 0, \\
 \left[ \rho V_n^2 + P + \frac{B^2}{2\mu_0} \right] &= 0, \\
 \left[ \rho V_n \mathbf{V}_t - \frac{B_n \mathbf{B}_t}{\mu_0} \right] &= 0, \\
 \left[ \rho V_n \left( \frac{V^2}{2} + \frac{\gamma}{\gamma-1} \frac{P}{\rho} \right) + \frac{V_n B^2}{\mu_0} - \mathbf{V} \cdot \mathbf{B} \frac{B_n}{\mu_0} \right] &= 0, \\
 [V_n \mathbf{B}_t - B_n \mathbf{V}_t] &= 0, \\
 [B_n] &= 0.
 \end{aligned} \tag{1.7}$$

In the above,  $\rho$  is the plasma mass density,  $\mathbf{V}$  the bulk velocity vector,  $P$  the thermal pressure,  $\mathbf{B}$  the magnetic field vector. Subscripts n and t denote vector components normal and tangential to the shock surface. Square brackets denote the change in property from upstream to downstream of the shockfront. Note that these formulae are given in the rest frame of the shock.

Much of a shock's characteristics are controlled by  $\theta_{Bn}$ , the angle between the magnetic field and the shock normal. A shock for which  $\theta_{Bn} = 0^\circ$  is said to be parallel, while  $\theta_{Bn} = 90^\circ$  is a perpendicular shock. In most contexts, a shock is rarely perfectly perpendicular or parallel, and is said to be oblique. In this case, the jump conditions can be applied. If this angle is low ( $< 45^\circ$ ), the shock is said to be quasi-parallel, whereas if it is high ( $> 45^\circ$ ), it is said to be quasi-perpendicular. This is illustrated in Figure 1.1. In quasi-perpendicular shocks particles are generally unable to escape upstream, as their gyration around the impinging field lines leads them back into the shock front. In quasi-parallel shocks, however, the field geometry is such that there is a significant degree of reflected particle escape upstream (Baumjohann and Treumann,

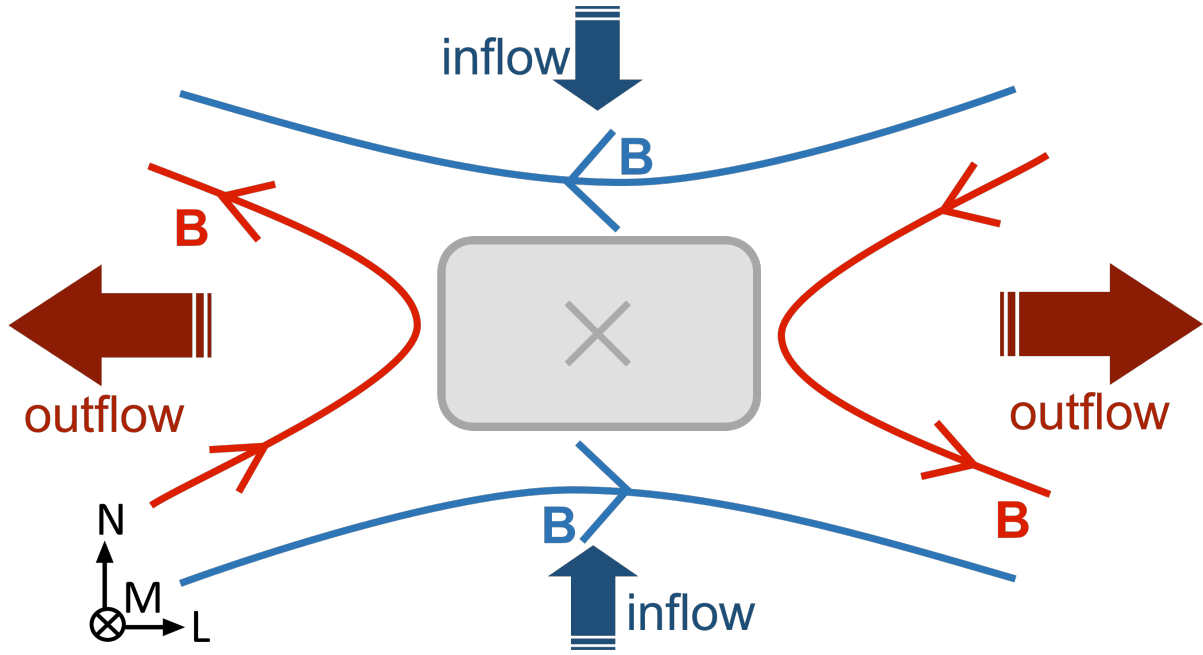


**Figure 1.1:** Cartoon illustrating particle reflection at a) quasi-parallel, and b) quasi-perpendicular shocks. In both, the left hand side represents the upstream region, with downstream on the right. Solid green line represents the shock front, with surface normal  $\hat{n}$ . Black arrow depicts magnetic field orientation, with the angle between field and shock normal denoted  $\theta_{Bn}$ . Magenta line illustrates reflected particle motion. In the quasi-parallel case, particles gyrate around the field line and are able to escape upstream, while in the quasi-perpendicular case their gyration leads them back into the shockfront with no escape.

2022). This makes the quasi-parallel shock transition more complicated than the quasi-perpendicular regime, with a large degree of structure formation possible upstream. This is the case in Earth’s foreshock (see Section 1.2.2).

### 1.1.3 Magnetic reconnection

Magnetic reconnection is a fundamental plasma process during which stored energy is released from magnetic fields by the instantaneous breaking and topological rearranging of field lines (see, e.g., Priest and Forbes (2000) for further information). A simplified diagram of the process is shown in Figure 1.2. It is generally understood to involve the annihilation of antiparallel magnetic field lines at a current sheet, that is, a thin boundary layer separating the two oppositely-oriented fields. When the two opposing plasmas (blue inflow in Figure 1.2) collide, the current sheet is compressed. When thinned to ion scales (of the order of the ion inertial length, Equation 1.6), the



**Figure 1.2:** Cartoon showing a basic picture of magnetic reconnection. Antiparallel field lines (blue) inflow and reconnect in the diffusion region (grey), producing high-speed outflow regions with field rotations (red). Shown in an LMN coordinate system (further detail in Section 2.3.3).

frozen-in field theorem no longer holds, enabling field lines to diffuse and lose their identity in a space known as the diffusion region. This is illustrated by the grey area in Figure 1.2. We picture the inflow fields as breaking and reconnecting with changed orientation, linking the fields across the current sheet. These newly-born field lines (red in Figure 1.2) are then accelerated away from the reconnection centre (X-point) by magnetic tension, typically with higher speed and temperature than the inflow regions. We call these fast plasma flows reconnection exhausts or outflows. Note that the term ‘jet’ is often used in literature to describe a reconnection exhaust however we shall refrain from using that in this thesis, so as to avoid confusion with magnetosheath jets.

Early ideas of reconnection were proposed by Dungey (1953), and refined by Parker (1957) and Sweet (1958) in what became known as the Sweet-Parker reconnection model. Another early interpretation included that of Petschek (1964), which modified the Sweet-Parker model to greatly reduce the size of the required diffusion region and increase the allowed reconnection rate. These two models rely on the particle collisions in resistive MHD. Modern interpretations, however, reformulate this for collisionless

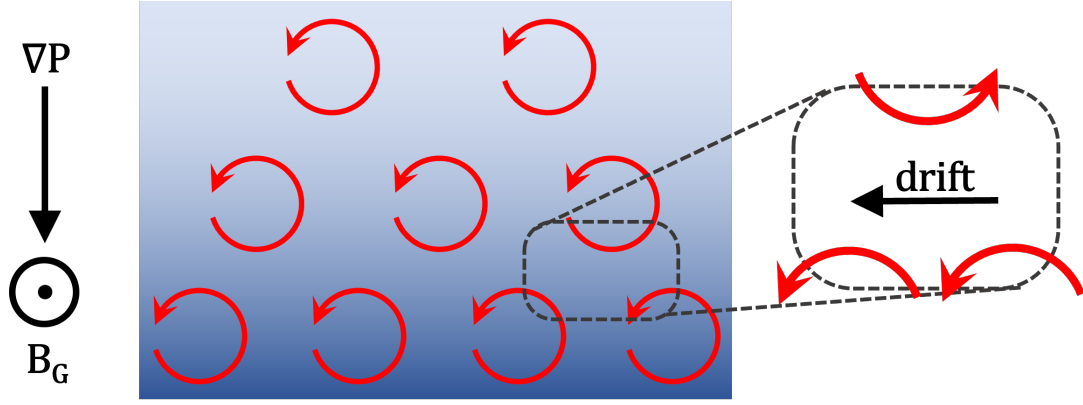
plasmas (Vasyliunas, 1975) and include Hall physics (e.g., Hesse et al., 2001). More recently, our understanding of reconnection has vastly increased in complexity thanks, in no small part, to the extremely high-resolution data made available by the Magnetospheric Multiscale mission (MMS; Burch et al., 2016). This has made it possible to study reconnection in a variety of other guises and contexts, such as electron-only reconnection (e.g., Phan et al., 2018), high-guide field (out of plane) reconnection (e.g., Øieroset et al., 2016), and the interplay of reconnection and turbulence (e.g., Stawarz et al., 2019). The details of these processes are generally beyond the scope of this thesis, suffice to say that magnetic reconnection is a highly active and developing field of research.

Theory and simulation (Swisdak et al., 2003; Swisdak et al., 2010) have shown that the onset of magnetic reconnection can be prevented by the influence of asymmetries. A pressure gradient across the current sheet coupled with a guide field, that is, a net out-of-plane magnetic field resulting from inflow fields that are not perfectly antiparallel, can induce a diamagnetic drift in the plasma. The cause of the drift can be visualised conceptually by considering the density of gyrating particles, which is illustrated in Figure 1.3. In any fluid element, there is a imbalance in the lateral motion, thus creating a net drift, which is to the left in Figure 1.3. The diamagnetic drift velocity is given by

$$\mathbf{V}_{\text{diamagnetic}} = \frac{\mathbf{B}_G \times \nabla_{\perp} P}{qnB_G^2} \quad (1.8)$$

where  $\nabla_{\perp} P$  is the pressure gradient perpendicular to the guide field,  $\mathbf{B}_G$ , and  $q$  the particle species charge. This means that positive ions and negative electrons are subject to oppositely directed drifts. The net drift speed of the X-line relative to the ions is therefore the sum of these two drifts (Eastwood et al., 2013).

Swisdak et al. (2003) theorised that reconnection is suppressed if this drift speed exceeds the exhaust outflow speed, which is considered to be of the order of the Alfvén speed. Figure 1.4a illustrates this effect for reconnection at the magnetopause where there is a strong density gradient (see Section 1.3). The drift occurs in the direction of the outflows, and so if the X-line is unable to form for a drift speed higher than the



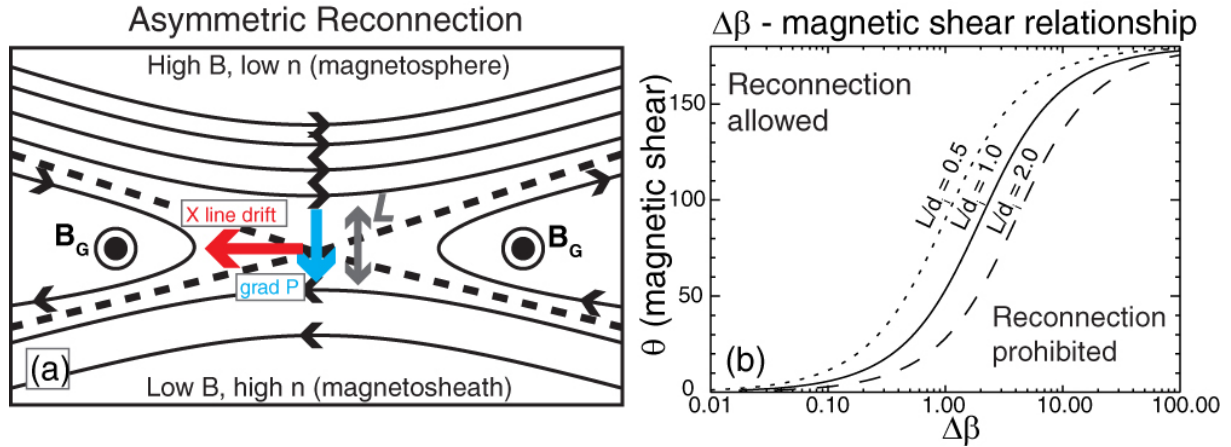
**Figure 1.3:** Illustration demonstrating the origin of diamagnetic drift under a pressure gradient and guide field, shown for electrons. Red arrows show particle gyration. In each fluid element, the density gradient is such that there is a net drift to the left. After Baumjohann and Treumann (2022).

characteristic exhaust speed. Swisdak et al. (2003) showed that this condition can be expressed as

$$\Delta\beta > 2(L/d_i) \tan(\theta/2), \quad (1.9)$$

where  $\Delta\beta$  is simply the difference in plasma  $\beta$  (Equation 1.1) between the reconnecting plasmas, while the shear angle denotes the angle between magnetic field vectors either side of the current sheet, and  $L/d_i$  is the pressure gradient scale length, comparable to the X-line width, in units of ion inertial lengths. A shear of  $180^\circ$  represents antiparallel field vectors, which is the traditional view of reconnection (as in Figure 1.2). These parameters therefore control the onset of reconnection. This dictates that, as perhaps would be expected, that low shear angles are unfavourable for reconnection, as is having a large  $\beta$  asymmetry. A smaller value of the scale size parameter  $L$  increases the likelihood of reconnection suppression. This can be thought of as a sharper pressure gradient producing a stronger drift and suppressive effect.

This provides a necessary, but not sufficient, condition for reconnection to occur. In other words, reconnection should always be suppressed when Eq 1.9 is satisfied, but it is not guaranteed that reconnection will be triggered if the conditions are reversed. It may be the case that other factors (e.g., current sheet thickness or time-variability) prevent the onset of reconnection even in favourable  $\Delta\beta$ -shear conditions. Figure 1.4b shows the  $\Delta\beta$ -shear angle parameter space and the regions for which reconnection is



**Figure 1.4:** a) Illustration of diamagnetic X-line drift under a pressure gradient (grad P) and guide field ( $B_G$ ). b) Regions of  $\Delta\beta$ -shear angle parameter space for which reconnection is allowed or prohibited, shown for several values of  $L/d_i$ . From Eastwood et al. (2013).

permitted or prohibited, for multiple values of  $L/d_i$ . In Section 1.3 we describe studies that test this theory with spacecraft observations.

## 1.2 The Sun, solar wind, and magnetosphere

### 1.2.1 Heliophysics

The Sun's influence pervades the solar system, not only due to its light and gravitational pull, but also by virtue of its magnetic field and plasma outflow. We call this outflow the 'solar wind'. It extends far into space, and all solar system bodies are immersed in its flow. As the solar wind streams outwards, it carries the Sun's magnetic field with it, which we call the interplanetary magnetic field (IMF). The region of space occupied by the solar wind's extent is called the heliosphere, and much of the behaviour of the bodies within it is controlled by the IMF. Solar and heliophysics physics are extremely wide and diverse research areas, most of which is beyond the scope of this thesis. Here we will simply touch on a few key aspects of relevance to the work that follows.

The solar wind can broadly be categorised into two types — fast and slow solar wind. Fast solar wind is generally thought to originate from coronal holes, 'gaps' in the Sun's upper atmosphere where open field lines emerge, whereas slow solar wind is believed

**Table 1.1:** Typical properties of fast and slow solar wind at 1 AU

| Property                     | Slow wind  | Fast wind |
|------------------------------|------------|-----------|
| Speed ( $\text{km s}^{-1}$ ) | 300–500    | 600–800   |
| Density ( $\text{cm}^{-3}$ ) | 7–15       | 1–7       |
| Temperature (eV)             | $\sim 3.5$ | $\sim 17$ |

*Note.* Values refer to bulk ion properties. Values taken from Russell et al. (2016).

to emerge from closed field line regions, typically near the solar equator. Some typical properties of fast and slow solar wind measured near Earth are given in Table 1.1. In general, the near-Earth solar wind can be considered to be high-speed and rarefied, with typical field strengths of around 5 nT. This makes the  $\beta$  reasonably low, typically of the order of unity at 1 AU, therefore the plasma flow and magnetic field are strongly coupled.

As the Sun rotates and solar wind propagates radially, the IMF becomes wound into a spiral (known as the Parker spiral). Due to its higher speed, fast solar wind therefore typically results in a more radial field pattern than the slow solar wind. This variability can occasionally result in the formation of a large compressive structure known as a stream interaction region (SIR), where fast solar wind streams catch up with patches of slow solar wind (see, e.g., Richardson, 2018).

The solar wind and IMF are highly variable. As well as a great degree of flow fluctuation, the solar wind is often disturbed by the presence of large transients such as coronal mass ejections (CMEs) which propagate in interplanetary space as large flux ropes (see, e.g., Good et al., 2019). These large eruptions of plasma from the Sun often possess more extreme properties than can be seen in the ambient solar wind, such as high speeds, densities, and magnetic field strengths. Upon impacting planetary bodies, they have the ability to significantly disturb magnetospheric dynamics (see next section).

As well as short-term variation, some properties of the solar wind are modulated on longer timescales by the solar cycle (see, e.g., Hathaway, 2015). This 11 year cycle in solar activity can change the frequency of eruptive events like CMEs and flares



(intense bursts of radiation and energetic particles), as well as the structure of the Sun's magnetic field and solar wind streams. At solar minimum, it is typically expected that the Sun maintains an ordered dipole-like structure with coronal holes near the poles and closed field lines at the equator. At solar maximum, however, the structure becomes more disordered and coronal holes and fast streams are seen at a variety of solar latitudes, meaning that the proportion of fast solar wind expected to reach Earth would be higher than at solar minimum (McComas et al., 2003).

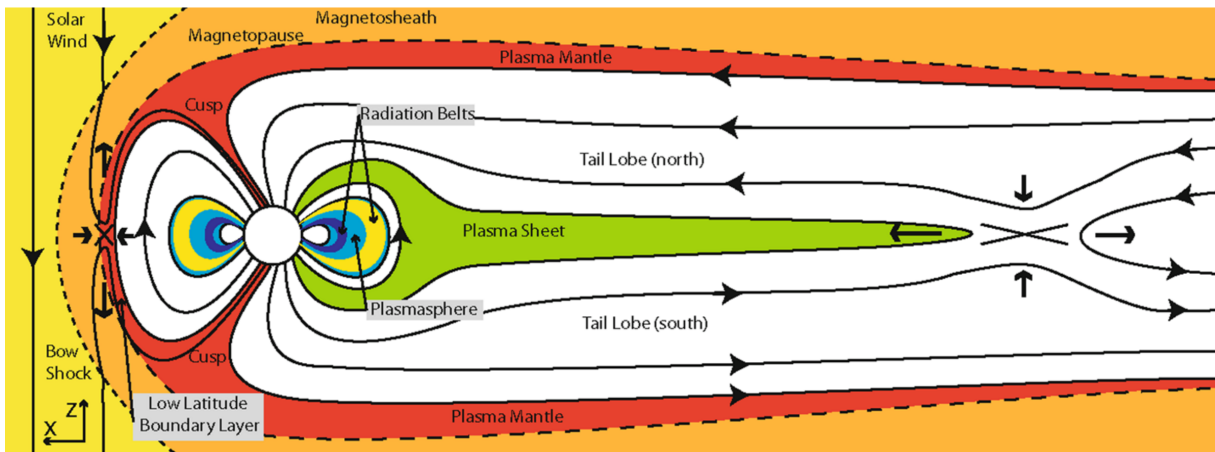
### 1.2.2 The terrestrial magnetosphere

The Earth's magnetic field extends far beyond the planet's surface, containing magnetised plasma within it. When the solar wind hits, the two plasmas are unable to interpenetrate due to their frozen-in fields. This carves out a protective magnetic cavity in the solar wind, called the magnetosphere. Several other bodies in the solar system are known to have magnetospheres, such as Mercury, Saturn, Jupiter, and the ice giants, all with unique structures and dynamics (see, e.g., Kivelson and Bagenal, 2014). In this thesis, we will focus on the terrestrial magnetosphere, a complete description of which can be found in many textbooks such as that by Russell et al. (2016).

A schematic of the magnetosphere is shown in Figure 1.5. The point of pressure balance between solar wind and magnetospheric plasmas is known as the magnetopause, the position of which is constantly in motion due to the variable dynamic pressure of the impinging solar wind. For empirical models on the magnetopause position see Section 2.3.1. On the dayside, the magnetopause is pressed close to Earth (typically  $\sim 10 R_E$  at the nose), while on the nightside it extends outward, enclosing the magnetic field which is itself dragged out in the direction of solar wind flow, forming a long magnetotail.

The solar wind speed near Earth is super-fastmagnetosonic, that is, greater than the local wave speed (typically  $M_A \sim 10$ ). This means that the magnetosphere acts as an obstacle immersed in a supersonic flow, and a curved bow shock forms upstream. Shocked plasma flows between the bow shock and the magnetopause in a hotter,

turbulent layer called the magnetosheath (orange region in Figure 1.5). This layer, of thickness around  $2\text{--}3 R_E$  on the dayside, is the main region of study in this thesis. In the magnetosheath, densities are typically of the order of  $\sim 30 \text{ cm}^{-3}$ , temperatures around 200 eV, and magnetic field magnitudes of  $\sim 30 \text{ nT}$ . The typical  $\beta$  in the dayside magnetosheath is on the order of 10. The plasma flow velocity downstream of the shock is slower than the solar wind approximately by a factor of four. In the subsolar region (close to the Sun-Earth line) it is understood to slow further, reaching a stagnation point at the magnetopause as the plasma piles up, with an approximately linear velocity gradient from bow shock to magnetopause (Sibeck et al., 2022). Away from the nose, the magnetosheath plasma flow generally follows the curvature of the magnetopause.



**Figure 1.5:** General structure of the terrestrial magnetosphere. Arrows show magnetic field line polarities, and crosses mark sites of magnetic reconnection. From Eastwood et al. (2015).

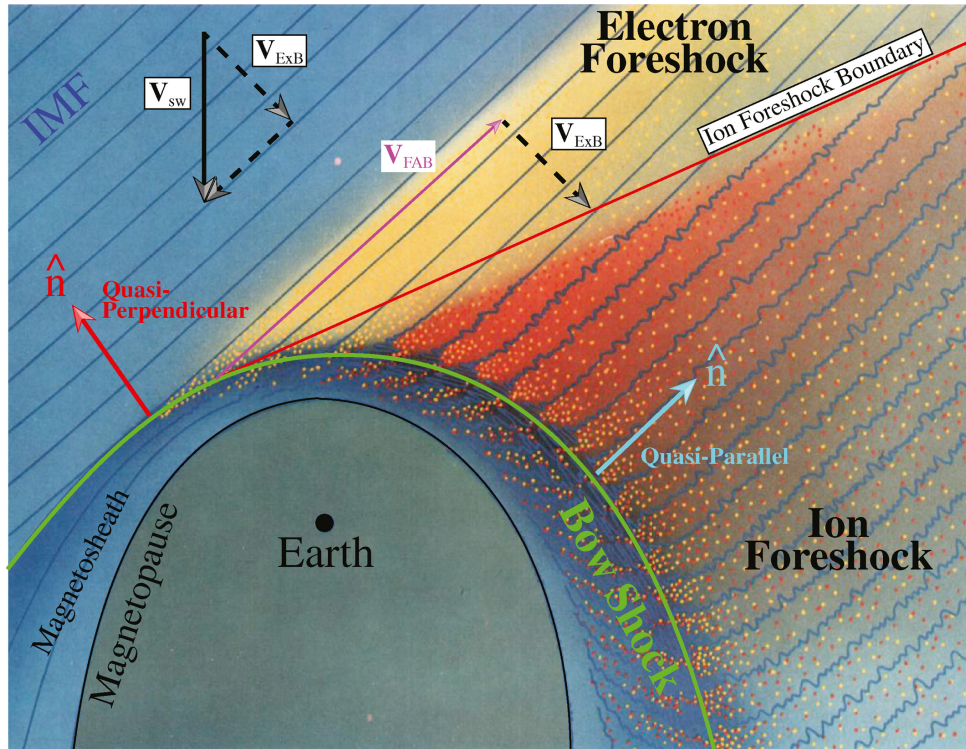
The magnetosphere is innately coupled with the solar wind and IMF. A mechanism first proposed by Dungey (1961), the so-called Dungey cycle, explains the solar-terrestrial link and global magnetospheric dynamics via a series of magnetic reconnection events. If the IMF is incident on the dayside magnetopause with a component antiparallel to the geomagnetic field, that is, primarily southward (downwards in Figure 1.5; negative  $B_{Z,GSM}$ , see Section 1.2.4), magnetic reconnection can take place at the nose. This forms a connection between the IMF and magnetospheric field. This is marked by a cross on the left of Figure 1.5. The newly reconnected field lines are then advected antisunward by the solar wind flow, eventually draping over the magnetotail. Under extended periods of southward IMF, the amount of flux in the magnetotail rises until the antiparallel

fields of the north and south lobes are able to reconnect (right of Figure 1.5). Explosive reconnection exhausts drive closed field lines back towards Earth, where they will later co-rotate back to the dayside to begin the process again. Magnetic reconnection can therefore be thought of as the fundamental driver of magnetospheric dynamics.

Due to both the curvature of the shockfront and the variability of the IMF direction, the bow shock simultaneously has quasi-parallel and quasi-perpendicular regions. As described in Section 1.1.2, particle reflection at quasi-parallel shocks allow for a degree of structure formation upstream. We call this area the foreshock (see, e.g., Eastwood et al., 2005). It is a region that is magnetically connected to the quasi-parallel shock and contains a multitude of waves, energetic particles, and coherent structures that propagate both with and against the solar wind. This is illustrated in Figure 1.6. For an overview of various foreshock transients we refer the reader to the review of Zhang et al. (2022), though we note some examples include Short Large Amplitude Magnetic Structures (SLAMS; Schwartz and Burgess, 1991), hot flow anomalies (HFAs; Schwartz, 1995), and foreshock bubbles (Omidi et al., 2010). These structures interact with the quasi-parallel shockfront, making it a complex patchwork awash with turbulence and waves. Consequently, the quasi-parallel shock transition is less well-defined than the sharp boundary seen at the quasi-perpendicular shock (see, e.g., Blanco-Cano (2010) for a comparison). Due to IMF variability, the position of the foreshock on the bow shock is also variable. During times of quasi-radial IMF (low cone angle, defined in Section 1.2.4), the foreshock sits directly upstream of the bow shock nose in the subsolar region. We will go on to see that this configuration is highly important for the formation of magnetosheath jets.

### 1.2.3 Space weather

Space weather is an umbrella term for the set of phenomena experienced on or near Earth that has an impact on life and technology, as a result of the solar-terrestrial link (see, e.g., Hapgood, 2011; Eastwood et al., 2017b; Schwenn, 2006). The Sun,



**Figure 1.6:** Illustration of Earth's foreshock shown in the X-Y plane. Backstreaming particles at the quasi-parallel shock form a region upstream dominated by waves and coherent plasma structures. Taken from Wilson III et al. (2021), original version from Tsurutani and Rodriguez (1981).

solar wind, and transient structures such as coronal mass ejections can influence space weather through driving the Dungey cycle, compression of the magnetosphere by high dynamic pressures, and by cascades of energetic particles. This, in turn, can influence the radiation belts (regions of highly energetic particles within the inner magnetosphere), ionosphere (the ionised part of the upper atmosphere), and the Earth's surface. Extensive details of the mechanisms and ramifications are not presented here but in general, space weather can present a significant risk to technology, infrastructure, and life. Observed and predicted effects are as dramatic and diverse as mass power grid failure, as occurred in 1989 in Quebec (Bolduc, 2002), GPS blackouts (Kintner et al., 2007), and corrosion of underground pipelines (Viljanen et al., 2006). While scientific foundations for the physical understanding of space weather are reasonably well developed, strategies of risk analysis and disaster mitigation in society are still in relatively early stages (Eastwood et al., 2017a).

Space weather forecasting relies on monitoring the Sun and solar wind using a com-

bination of remote sensing and in situ observations. By imaging the Sun, we are able to track active regions (sunspots) in the photosphere where particularly strong and kinked magnetic fields increase the likelihood of eruptive events, such as flares and CMEs. This is the aim of missions such as the Solar and Heliospheric Observatory (SOHO; Domingo et al., 1995), the twin spacecraft of the Solar Terrestrial Relations Observatory (STEREO; Kaiser et al., 2008), and the more recent Solar Dynamics Observatory (SDO; Pesnell et al., 2012). To predict the magnetospheric response to the impact of solar wind transients, however, it is useful to have in situ measurements. As well as determining speed and pressure likely to be exerted on the magnetosphere, this allows the magnetic field orientation to be measured. If strongly southward for prolonged periods, then strong driving of the Dungey cycle is to be expected. Spacecraft used for this typically reside at L1 — the Sun-Earth Lagrange point shortly upstream of Earth — and include Wind (Lepping et al., 1995) and the Advanced Composition Explorer (ACE; Stone et al., 1998). Further details on how these spacecraft are used to understand the near-Earth solar wind are given in Chapter 2.

### 1.2.4 Coordinate systems and terminology

In this thesis, we will use two main coordinate systems to represent the magnetosphere. These are the geocentric solar ecliptic (GSE) system, and the geocentric solar magnetic (GSM) frame. The GSE coordinate system is centred on Earth, with its X axis pointed sunward. The Y axis lies in the ecliptic plane, pointed duskward, opposite to the direction of planetary motion, and the Z axis completes the orthogonal set, parallel to the ecliptic pole. This coordinate system is often used when studying the near-Earth solar wind and dayside outer magnetosphere. The GSM system shares its X axis with GSE. The Y axis is such that it is perpendicular to the Sun-Earth line and Earth's magnetic dipole, with the Z axis completing the right-handed set in the plane containing the Sun-Earth line and the dipole (e.g., Laundal and Richmond, 2017). GSM is typically used when studying the magnetopause, magnetotail, and inner magnetosphere.

An important metric used throughout this thesis is the IMF cone angle. We define this as the acute angle between the IMF and the Sun-Earth line. It is therefore given by

$$\alpha = \cos^{-1}(B_{X,\text{GSE}}/B), \quad (1.10)$$

for IMF magnitude  $B$ . Note that it is the X-component of the field which chiefly controls the cone angle, effectively making it a measure of IMF obliquity, with a low cone angle corresponding to quasi-radial IMF. Note that is different to the IMF clock angle, which indicates the IMF direction in the Y-Z plane.

In the subsolar region of the magnetosheath, that is, the area closest to the Sun-Earth line, the cone angle is approximately similar to the field-shock normal angle ( $\theta_{Bn}$ ). In this sense, low cone angles ( $0 - 45^\circ$ ) correspond to the quasi-parallel shock, while high cone angles ( $45 - 90^\circ$ ) correspond to the quasi-perpendicular shock.

## 1.3 Reconnection at the magnetopause

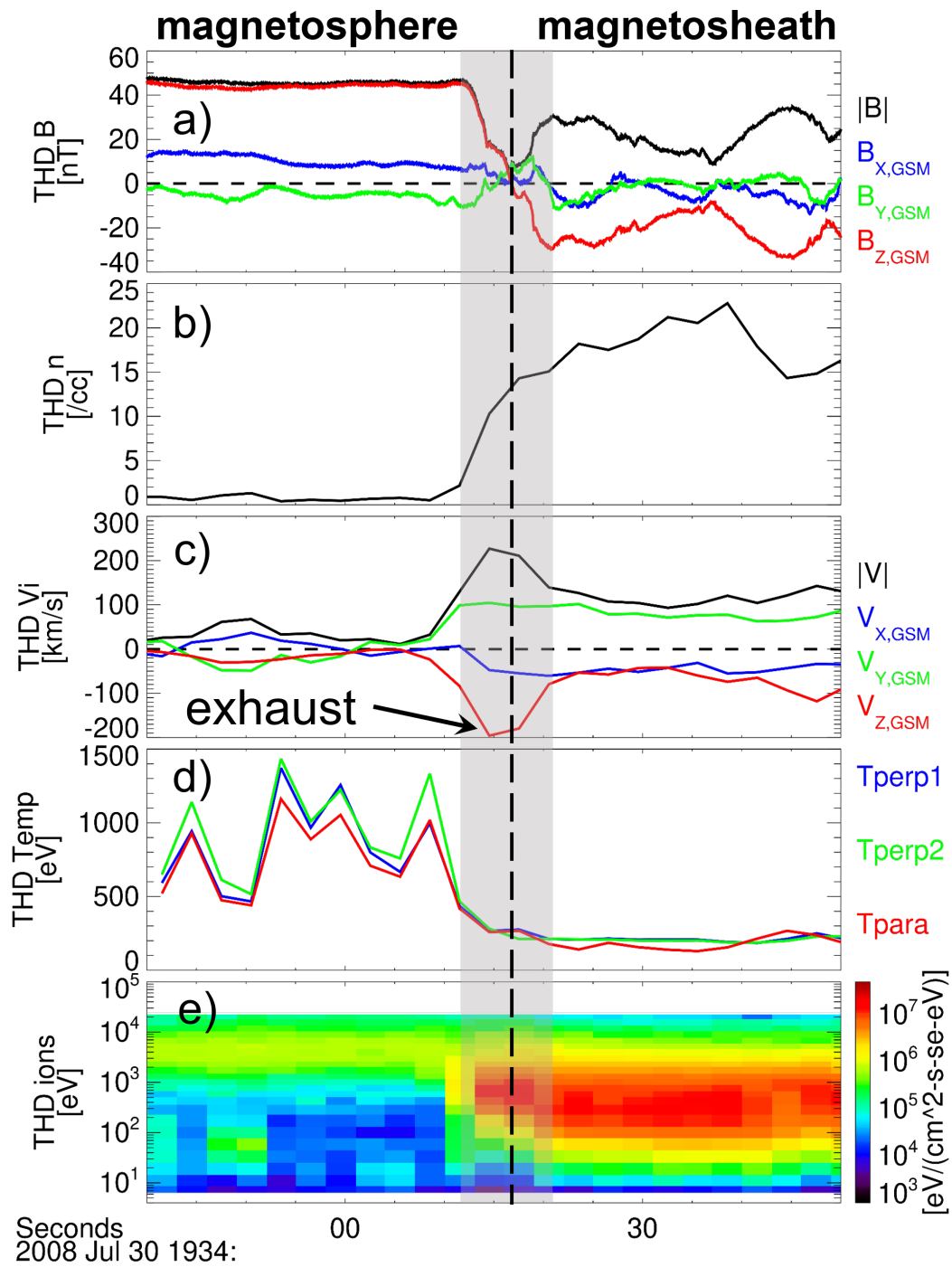
Magnetic reconnection at Earth's magnetopause is one of the most extensively studied aspects of space plasma physics. Much of this has been possible due to the launch of multi-spacecraft missions, particularly Cluster (Escoubet et al., 2001). This was later supported and furthered by the Time History of Events and Macroscale Interactions during Substorms mission (THEMIS; Angelopoulos, 2008; further details in Chapter 2), and more recently the Magnetospheric Multiscale mission (MMS; Burch et al., 2016).

### 1.3.1 Magnetopause reconnection in spacecraft data

Figure 1.7 shows an example time series plot of magnetic field and ion observations from the THEMIS D spacecraft (THD, see Section 2.1.1) crossing the magnetopause and observing reconnection taking place. Here we can see several characteristics of a typical magnetopause crossing. The left side of the plot shows the magnetosphere, while the right shows measurements of the magnetosheath. The magnetopause region

is illustrated by the grey region, which bounds the  $B_Z$  rotation, while the vertical dashed line marks the point of minimum  $|B|$ , which can be regarded as the X-line. Inside the magnetosphere we see that the magnetic field is strongly positive (northward) in the GSM-Z direction (Figure 1.7a), as would be expected from the geomagnetic field. As the spacecraft passes from the magnetosphere to the magnetosheath the field magnitude decreases. In the magnetosheath, the  $B_Z$  can be northward or southward, though in this case it is strongly southward. Magnetosheath magnetic fields typically display a higher degree of small-scale fluctuation than the magnetosphere, which can also be seen here. We can see in Figure 1.7b that the magnetosheath possesses a much higher density than the magnetosphere, as well as generally greater plasma flow speeds (Figure 1.7c). Due to higher energy particles, the temperature inside the magnetosphere is significantly greater than in the magnetosheath (Figure 1.7d). This also is reflected in the ion spectrogram (Figure 1.7e) where we see that the magnetosheath possesses a much greater density of mid-level energy ions compared to the magnetosphere, which is primarily comprised of particles in the highest energy ranges.

As well as typical magnetopause characteristics, Figure 1.7 also shows some of the features from which reconnection can be identified. Across the magnetopause, the magnetic field in Figure 1.7a undergoes a rotation in the Z-component. This characteristic Z-shape signals a current sheet with near-antiparallel fields on either side. The other key reconnection signature visible is the strong velocity enhancement in the negative Z direction (Figure 1.7c). This shows the spacecraft crossing the reconnection exhaust, one side of the X-line. Reconnection exhausts are also typically denser and hotter than their surroundings. However, this is more visible when the reconnecting plasmas are symmetric, with near-equal densities on either side, which is not the case at the magnetopause. This is more commonly observed for reconnection in the solar wind (e.g., Gosling et al., 2005; Mistry et al., 2017), or within the magnetosheath (e.g., Retinò et al., 2007; Eastwood et al., 2018). Asymmetric conditions at the magnetopause modify the reconnection geometry from the symmetric model, leading to a separation of the X-line and stagnation point (e.g., Phan et al., 1996; Eastwood et al., 2013). This



**Figure 1.7:** Example time series of a magnetopause crossing and reconnection signature seen by THEMIS D (THD). a) magnetic field, b) density, c) velocity, d) temperature, e) ion energy spectrogram. Grey area marks the region in which there is a  $B_z$  rotation across the current sheet. Vertical dashed line marks the point of minimum  $|B|$ .



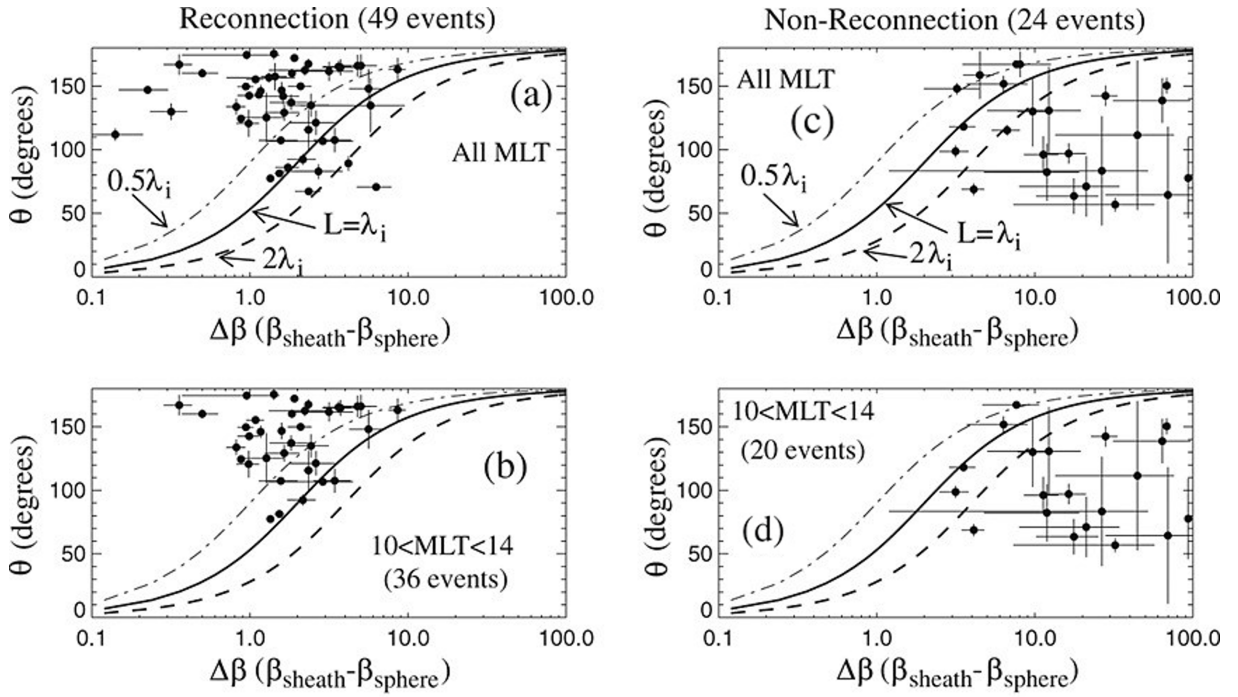
means that the  $B_Z$  rotation occurs largely within the high density (magnetosheath) region, and also has the effect of pushing the peak of the velocity exhaust to the low  $\beta$  side, i.e., the magnetospheric side. These effects can be seen in Figure 1.7.

### 1.3.2 Observational studies of the $\Delta\beta$ -shear relation

The  $\Delta\beta$ -magnetic shear relation (Eq 1.9; Swisdak et al., 2010), which developed primarily out of theory and simulation, has been tested and verified through observations. This was first done by Phan et al. (2010) using a survey of 197 reconnecting current sheets in the pristine solar wind as seen by the Wind spacecraft. Each reconnection event was characterised by its  $\Delta\beta$  and magnetic shear angle. They found the reconnection observations to be in very good agreement with the theoretical prediction. Later Gosling and Phan (2013) tested the relation on 9 current sheets driven by a fast coronal mass ejection. They found it to hold true and, in particular, yielded observations of reconnection occurring at current sheets with smaller shear angles than had previously been reported.

The relation has also been tested at the magnetopause. Phan et al. (2013) performed a similar analysis to their earlier Wind study, instead using a survey of magnetopause crossings seen by the THEMIS spacecraft. Figure 1.8 shows a key result from their study. Dividing each magnetopause crossing into reconnecting and non-reconnecting (and eliminating unclear cases), they placed their events in the  $\Delta\beta$ -shear angle parameter space. In each panel of Figure 1.8, the solid curve represents the limit of Eq 1.9 (taking  $L = 1 d_i$ ). The area above the curve is therefore the region where  $\Delta\beta < 2 \tan(\theta/2)$ , meaning reconnection is allowed. Similarly, below the line is there  $\Delta\beta > 2 \tan(\theta/2)$  and reconnection should be suppressed by the X-line drift. As can be seen in Figure 1.8, Phan et al. (2013) found good agreement between reconnection observations and the theoretical prediction. This is particularly true at magnetic local times (MLT) between 10 and 14, i.e., the subsolar region (Figures 1.8b and 1.8d).

Koga et al. (2019) also verified the relation in a study of 25 magnetopause crossings



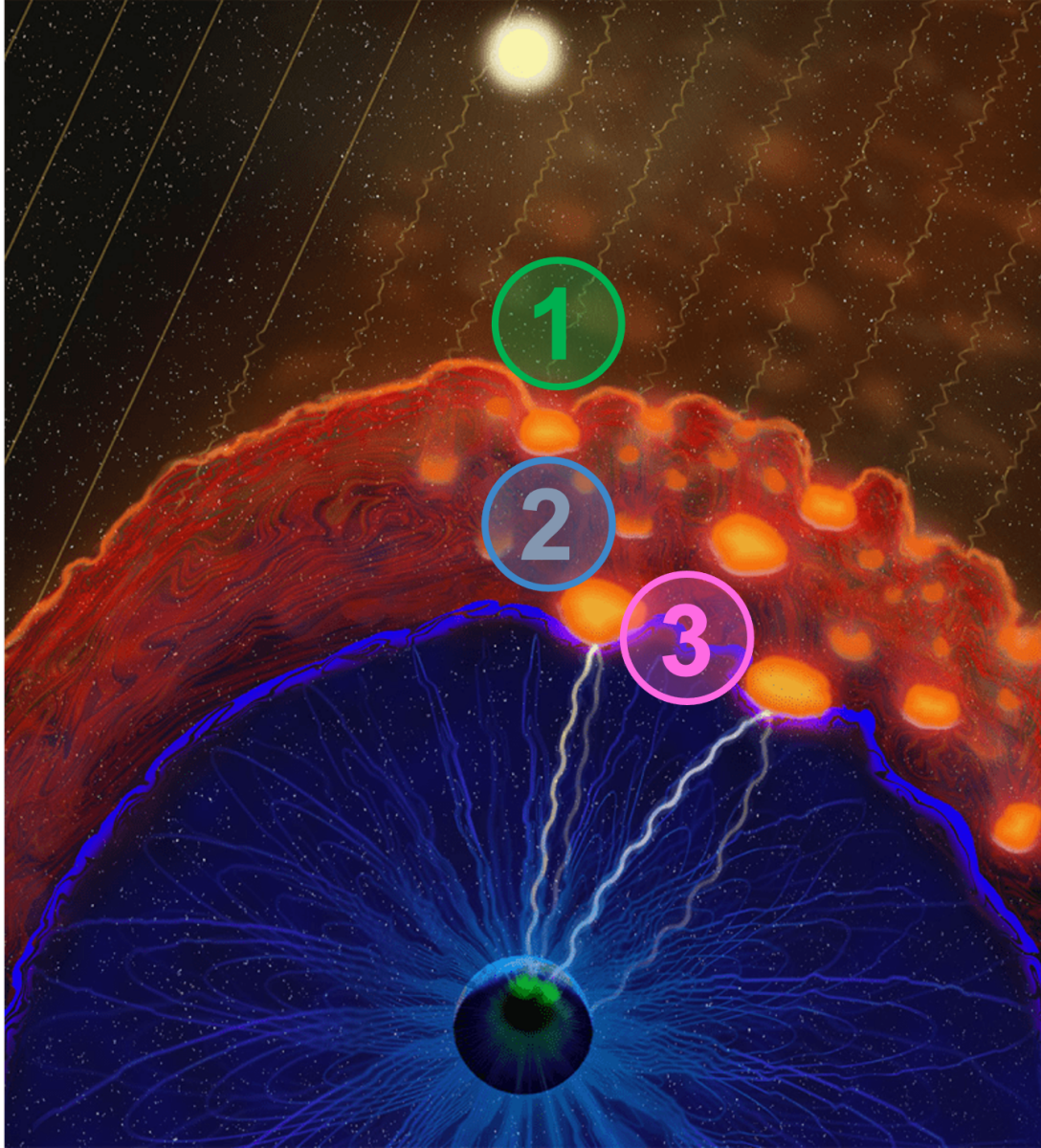
**Figure 1.8:** Scatter plots showing the magnetic shear and  $\Delta\beta$  of reconnecting (left) and non-reconnecting (right) magnetopause crossings. Solid line represents the limit of the  $\Delta\beta$ -shear condition, taking the pressure gradient width as one ion inertial length ( $\lambda_i$ , referred to as  $d_i$  elsewhere). Dashed lines show the same for  $L = 0.5 d_i$  and  $L = 2 d_i$ . Data points in the parameter space above the line are expected to be able to reconnect, while reconnection is expected to be suppressed for data below the line. Adapted from Phan et al. (2013).

seen by THEMIS, each of which had previously been reported in literature. They saw that reconnection events with high  $\Delta\beta$  were only observed for high shear angles. The condition has also been applied further afield. Masters et al. (2012) used it to predict the likely reconnection behaviour at Saturn. They concluded that, due to the high  $\Delta\beta$  usually seen there, reconnection is likely to be suppressed a majority of the time, meaning that the magnetosphere-solar wind interaction at Saturn cannot be assumed to be Earth-like. In this thesis, particularly Chapter 4 and Chapter 5, we will use this theory to study how reconnection may be affected by magnetosheath jets.

### 1.4 Magnetosheath jets

The main topic investigated in this thesis is magnetosheath jets (see Plaschke et al., 2018 and references therein for a comprehensive review). In literature they have taken on many guises, including as ‘high-speed jets’ (HSJs; Plaschke et al., 2013), ‘dynamic pressure enhancements’ (Archer and Horbury, 2013), or ‘plasmoids’ (Karlsson et al., 2015). In this thesis we shall simply refer to them as ‘jets’. We picture jets as localised high-dynamic pressure pulses observed in the magnetosheath, typically on scale sizes comparable to Earth. An illustration of this is shown in Figure 1.9. They are understood to originate at the bow shock and propagate Earthward through the magnetosheath towards the magnetopause.

The first recorded observations of what we might now call jets were made by Němeček et al. (1998), who termed them ‘transient flux enhancements’. The study of jets, however, did not gain significant momentum for a decade following that study. Early studies such as those by Hietala et al. (2009) and Shue et al. (2009) highlighted jets as a topic of interest to the community, with large statistical studies such as those by Archer and Horbury (2013) and Plaschke et al. (2013) shortly following.



**Figure 1.9:** Artist's impression of jets and their role in the dayside magnetosheath. Jets (orange blobs) form downstream of the quasi-parallel bow shock and propagate through the magnetosheath. Upon impacting the magnetopause, they may trigger reconnection and stimulate aurora. Numbers represent the three research questions investigated in this thesis and the regions of space to which they pertain (see Section 1.5). Image adapted from Vuorinen et al. (2021).

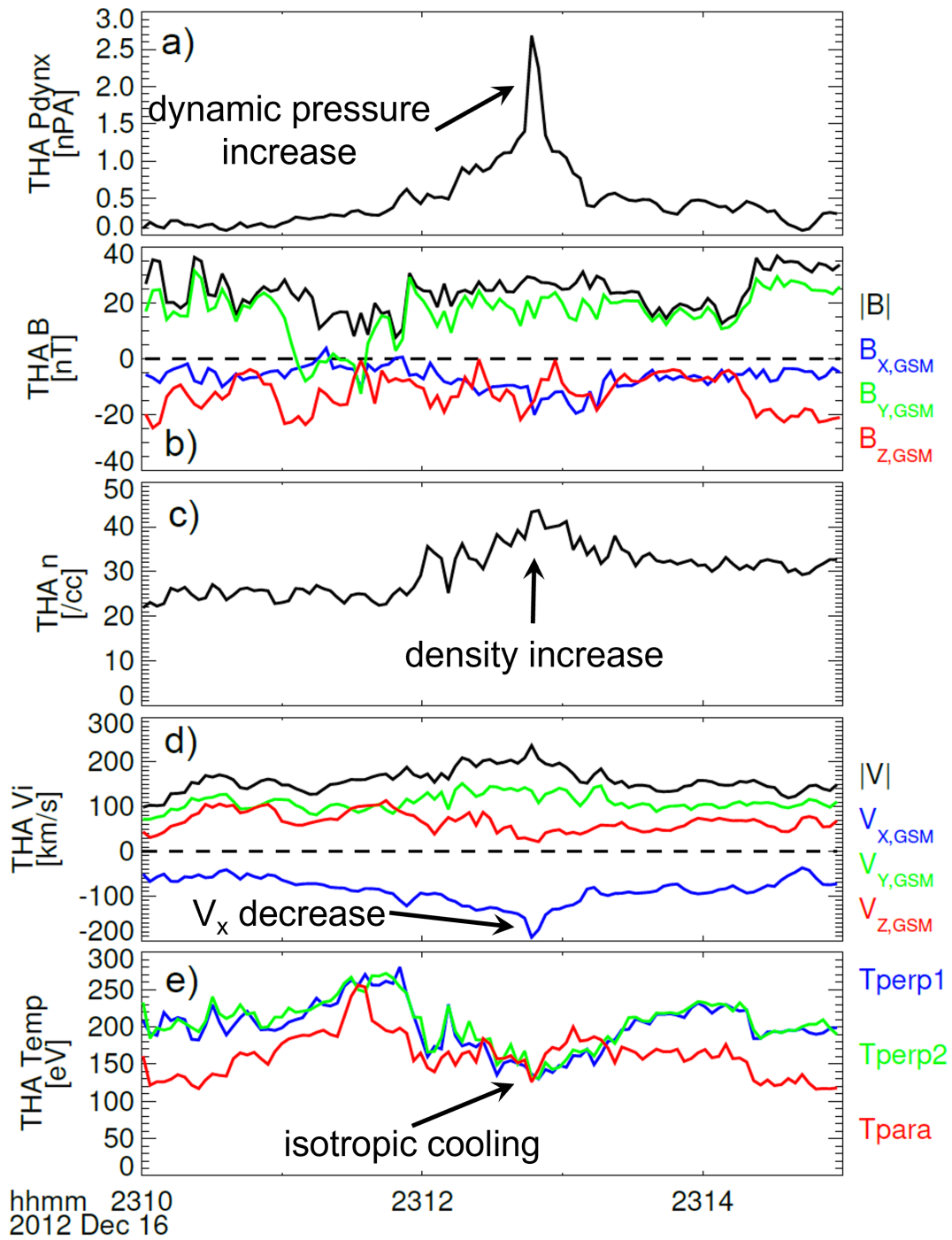
### 1.4.1 General concepts, properties, and definitions

While jet definitions and observed properties have varied somewhat in literature, there are some generally universally agreed characteristics. Figure 1.10 shows a time series plot of a typical jet observed in the magnetosheath by THEMIS A. The main identifying characteristic is the enhanced Earthward dynamic pressure ( $\rho V_X^2$ ), visible in Figure 1.10a. Jets do not typically display distinct magnetic field signatures (Figure 1.10b), though are often observed to contain a greater degree of field variability than the ambient magnetosheath. Dynamic pressure enhancements can be driven by either density, (Figure 1.10c), velocity (X-direction, Figure 1.10d), or both, as is the case in this example. They also often exhibit suppressed temperatures, particularly in the perpendicular components, so as to make the temperature more isotropic.

Statistical studies (e.g., Archer and Horbury, 2013; Plaschke et al., 2013), supported by simulations (e.g., Karimabadi et al., 2014; Palmroth et al., 2021), have elucidated these typical jet properties. However there is, by no means, a consensus on what an average jet looks like. In particular, different properties have been observed in different regions of the magnetosheath. Raptis et al. (2020) studied the differences between jets found downstream of the quasi-parallel shock versus those downstream of the quasi-perpendicular shock, finding that they display different properties, with quasi-perpendicular jets being generally weaker in terms of velocity, density, and duration.

In statistical studies, various different criteria for jet detection have been applied. For a thorough comparison, we refer the reader to the review of Plaschke et al. (2018), though we note some salient points here. Most recent jet literature adopts one of two approaches to jet definitions. Both of these use dynamic pressure as the key physical quantity, though the reference value providing the threshold differs. The definition generally attributed to Plaschke et al. (2013) is that a jet is identified when the X-directed dynamic pressure measured in the magnetosheath exceeds half that of upstream solar wind. That is,

$$\rho_{\text{msh}} V_{\text{msh},X}^2 > \frac{1}{2} \rho_{\text{SW}} V_{\text{SW}}^2. \quad (1.11)$$



**Figure 1.10:** Time series of magnetosheath jet observed by THEMIS A (THA). a) X-directed dynamic pressure, b) magnetic field, c) ion density, d) velocity, e) temperature (perpendicular and parallel components).

Archer and Horbury (2013), however, set their dynamic threshold based on a 20 minute running average of the magnetosheath dynamic pressure. They select jets when

$$\rho_{\text{msh}} V_{\text{msh}}^2 > 2 \langle \rho_{\text{SW}} V_{\text{SW}}^2 \rangle_{20 \text{ min}} \quad (1.12)$$

is fulfilled. Note also that they use the total magnetosheath velocity, rather than just the Earthward component. Most of the subsequent jet studies have used one of these criteria or close variants. For example, recently, Koller et al. (2022) modified the Archer and Horbury (2013) criterion to use only the X-directed velocity component, for easier comparison with the Plaschke et al. (2013) criterion, and to focus on jets propagating towards the magnetopause. They also increased the threshold factor from two to three to account for only using one velocity component. Note that throughout this thesis, unless explicitly stated otherwise, we define jets using the criteria of Plaschke et al. (2013). A full description of their selection process is given in Chapter 2.

Some studies of what we would now term jets have used detection thresholds based on physical quantities other than dynamic pressure, particularly density. This was done most notably by Karlsson et al. (2012) and Karlsson et al. (2015) (and later by Gutynska et al., 2015), who termed the transients ‘plasmoids’. They identified plasmoids where magnetosheath density satisfied

$$\rho_{\text{msh}} > \frac{3}{2} \langle \rho_{\text{msh}} \rangle_{300 \text{ s}}, \quad (1.13)$$

i.e., when 1.5x the 300 second running average of the magnetosheath density was exceeded.

In the review of Plaschke et al. (2018), the authors investigated the overlap in jets identified by the Plaschke et al. (2013), Archer and Horbury (2013), and Karlsson et al. (2012) criteria. Applying each to the data set of Archer and Horbury (2013) they found the overlap to be small, with fewer than 3 % of events identified being common to all three criteria. Despite this, however, they noted the properties and occurrence



behaviour exhibited by each data set to be similar. It is worth stating that there is no ‘correct’ jet definition. The different criteria enable different science questions to be investigated, and may in fact identify different phenomena, albeit with common traits.

Determining the size and morphology of jets is a non-trivial task, particularly when working with single spacecraft observations, and the typical spatial scales and shapes of jets are subjects of some debate. In observational studies a cylindrical geometry with axis-aligned velocity has generally been assumed. Estimates on their perpendicular diameter have ranged from  $0.1 R_E$  (Archer et al., 2012) to an upper limit of  $6 R_E$  (Hietala et al., 2012), though generally sit at or below  $1 R_E$  (Plaschke et al., 2018). Parallel lengths have been estimated at  $0.5 R_E$  (Němeček et al., 1998) to  $4.9 R_E$  (Gunell et al., 2014). It has typically been assumed that jets are greater in parallel extent than perpendicular, though Plaschke et al. (2016) found the reverse to be true, describing their morphology as ‘pancakes flying flat side first’. A different approach was taken by Karlsson et al. (2012) and Gutynska et al. (2015) who used minimum variance analysis (MVA; Sonnerup and Scheible, 1998; see Section 2.3.3) to determine sizes relative to the internal magnetic field axis, though these produced similar size estimates as above. More recently, Plaschke et al. (2020c) revisited the issue and used a statistical model to determine that jets may typically be smaller than previous estimates, though spacecraft observations naturally bias towards larger jets as they have a higher probability of being seen. They estimated the median jet sizes to be  $0.12 R_E$  in the perpendicular direction, and  $0.15 R_E$  in the parallel direction.

### 1.4.2 Jet origins, formation, and occurrence

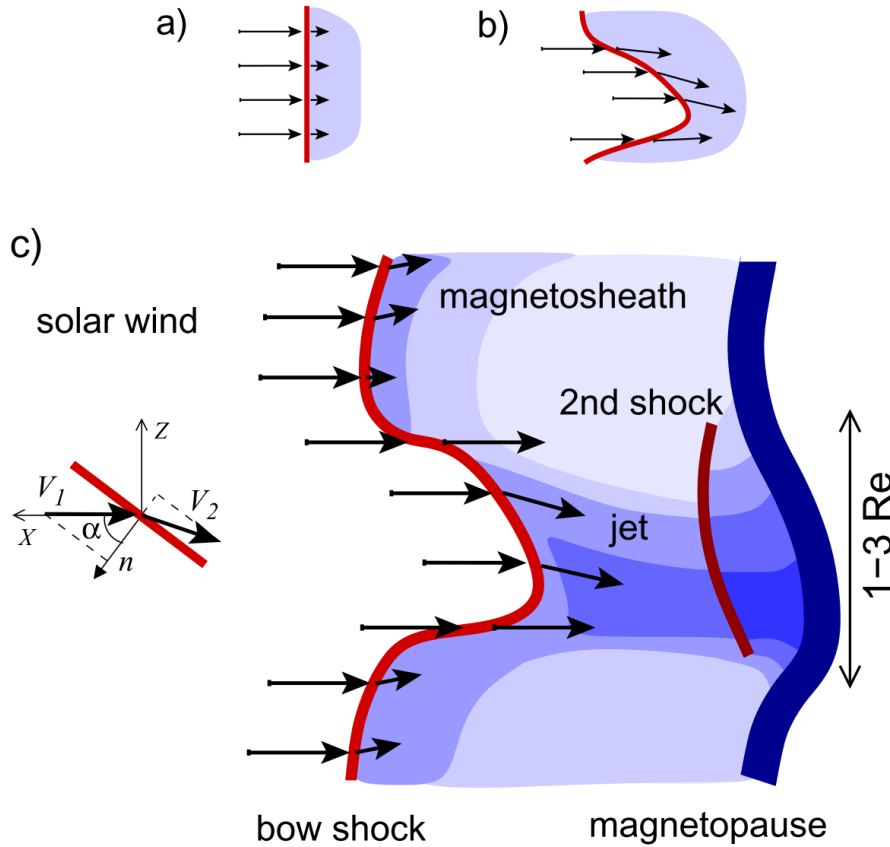
The origin of jets is still an active area of research without strong consensus. A variety of possible formation mechanisms have been proposed and observed. One prominent theory is that they form downstream of ripples in the bow shock. This idea was first suggested by Hietala et al. (2009) and refined by Hietala et al. (2012), though it has been explored by numerous authors. The proposed mechanism makes use of the Rankine-



Hugoniot jump conditions (Eq 1.7), which dictate the change in properties of an MHD flow crossing a shockfront. When crossing the shock, the velocity component normal to the shock surface is decelerated. The tangential component, however, remains approximately unaffected. The consequence of this is that local changes in shock inclination (ripples), where there is a significant tangential velocity component, cause the solar wind to be processed non-uniformly. There will, therefore, exist regions where the downstream flow is less decelerated than its surroundings. As the deflection angle varies across a ripple, the downstream density flow will also vary across the shock surface. This is illustrated in Figure 1.11. This theory is best applied to the subsolar region, where the solar wind flow is generally well aligned with the bow shock normal. In the flanks of the magnetosphere, however, the shock surface is more inclined, producing an average magnetosheath flow that is supermagnetosonic with respect to Earth.

The ‘ripple theory’ is supported by observational evidence. Hietala and Plaschke (2013) found that, in a data set of jets observed by THEMIS during times of quasi-radial IMF over a four year period, 97 % were consistent with being formed from bow shock ripples, and that these ripples need only be shallow undulations. They determined this by considering the theoretical maximum magnetosheath to solar wind dynamic pressure ratio allowed by varying degrees of shock tilt. Note that they did not claim to confirm that these jets did originate from ripples, only that the ripple mechanism could not be ruled out. Other observational studies have found supporting evidence for jets originating at ripples, such as that by Raptis et al. (2020), as well as several simulation studies (e.g., Karimabadi et al., 2014; Hao et al., 2016; Preisser et al., 2020). The origin of bow shock ripples themselves can be linked to the various structures observed upstream of the quasi-parallel shock, in the foreshock. When advected antisunward, these transient structures (such as SLAMS) can merge to form a patchwork shockfront with changes in local inclination.

Several other formation mechanisms have been proposed. These include the interac-



**Figure 1.11:** Cartoon demonstrating the ripple mechanism for jet production. Arrows depict solar wind flow velocity at different regions, the length indicating their magnitude. If the shock surface is a) planar, the flow is decelerated uniformly, but if it is b) rippled, flow is deflected but less decelerated downstream of more inclined surfaces. c) ripples across the bow shock can therefore create jets which, if supermagnetosonic, can drive secondary shocks in the magnetosheath. From Hietala et al. (2012).

tion of solar wind discontinuities with the bow shock (Archer et al., 2012; Dmitriev and Suvorova, 2012). While the associated numbers of jets observed to be consistent with this mechanism are dwarfed by those linked to bow shock ripples, Hietala and Plaschke (2013) and Archer and Horbury (2013) found that many of the jets that could not be explained by ripples (often those of particularly large amplitude) were in fact consistent with solar wind discontinuities. Many links have been drawn between jets seen in the magnetosheath and upstream foreshock transients. For example, foreshock compressive structures (FCSs) are transient features observed in the foreshock with strong dynamic pressure and magnetic field enhancements. Using a 2D hybrid simulation of the dayside magnetosheath, Suni et al. (2021) studied the interaction of FCSs with the bow shock. They saw that the transmission of an FCS through the shock

often resulted in jet-like structures being produced downstream. They also saw jets that were not formed by this mechanism, but the FCS-type jets dominated the occurrence statistics. This is in agreement with various other studies on foreshock transients. There is evidence to suggest that some jets may form from the interaction of SLAMS with bow shock ripples (Karlsson et al., 2015; Palmroth et al., 2018; Raptis et al., 2020). Connections have also been made between the transmission of foreshock bubbles and cavities through the shock (Archer et al., 2015; Sibeck et al., 2021).

Recently, Raptis et al. (2022) explored the idea that jets can be formed as a by-product of the reformation cycle of the bow shock, where parcels of solar wind-like plasma enter the magnetosheath having passed through a weakened shockfront at a step of its reformation cycle. This is in accordance with the simulation results of Omelchenko et al. (2021). This result is of great significance, as it provides a mechanism for jet generation as an inherent part of shock evolution.

It is worth noting that the lack of consensus on jet formation mechanisms is not necessarily troubling. In their most basic sense, jets are simply transient enhancements of dynamic pressure observed in the magnetosheath. It is no surprise, therefore, that a large variety of phenomena can be linked to this effect. The use of different jet definitions and identification criteria can bias some sources over others. For example, Plaschke et al. (2013) required the dynamic pressure enhancement to be in the X-GSE direction, whereas Archer and Horbury (2013) used total dynamic pressure. This means that the data set of Plaschke et al. (2013) was biased towards jets appearing to form at the bow shock (e.g., from ripples) and propagate Earthward, while the data set of Archer and Horbury (2013) also contains jets with other propagation directions and possible sources (e.g., reconnection exhausts or sunward flows driven by magnetopause oscillation). It is also likely true that the observations we call ‘jets’ in fact encompass multiple different phenomena with different properties. This can be seen when studying jets in the quasi-parallel magnetosheath versus those in the quasi-perpendicular region, and has been a recent area of research (e.g., by Raptis et al., 2020).

Over the past decade, there have been several large statistical studies on jet occurrence in the magnetosheath and with respect to the upstream solar wind conditions. Much of our understanding on jet occurrence (before the studies presented in this thesis) came from the studies of Plaschke et al. (2013) and Archer and Horbury (2013).

Plaschke et al. (2013) compiled a database of 2,859 jets seen by THEMIS and studied occurrence rates as a function of various upstream solar wind parameters. They found that the parameter that exhibited the strongest influence on the probability of jet observation was the IMF cone angle, with low cone angle solar wind strongly promoting jet occurrence. They noted minor dependencies on other solar wind quantities, with jet occurrence marginally more likely during times of high solar wind speed, high magnetosonic Mach numbers, and low density, though they could not state this conclusively without a greater number of observations. A similar analysis was performed by Archer and Horbury (2013), who also found a strong dependence on IMF cone angle and concluded that jets are an inherent feature of the quasi-parallel magnetosheath and therefore related to foreshock processes. They also saw a dependence on solar wind speed and IMF stability. Vuorinen et al. (2019), using the data set of Plaschke et al. (2013), analysed jet occurrence as a function of position in the magnetosheath. They found that jet occurrence is strongly dependent on the angle between IMF and shock normal ( $\theta_{Bn}$ ), with jets being approximately 9 times as likely to be observed downstream of the quasi-parallel shock compared to the quasi-perpendicular shock.

As a seemingly inherent feature of collisionless shocks, it should be expected that jets can occur in other shock environments than at Earth. This includes other planetary bow shocks such as Venus and Mercury, as well as shockfronts in interplanetary space, e.g., those driven by fast coronal mass ejections. Karlsson et al. (2016) investigated the possible evidence for jets at Mercury, with inconclusive results. As discussed in the review of Plaschke et al. (2018), the existence of jets at other shock environments is likely controlled by parameters such as the Alfvén Mach number and  $\beta$ , as well as typical IMF orientation. The bow shocks of Venus and Mars are known to exhibit relatively

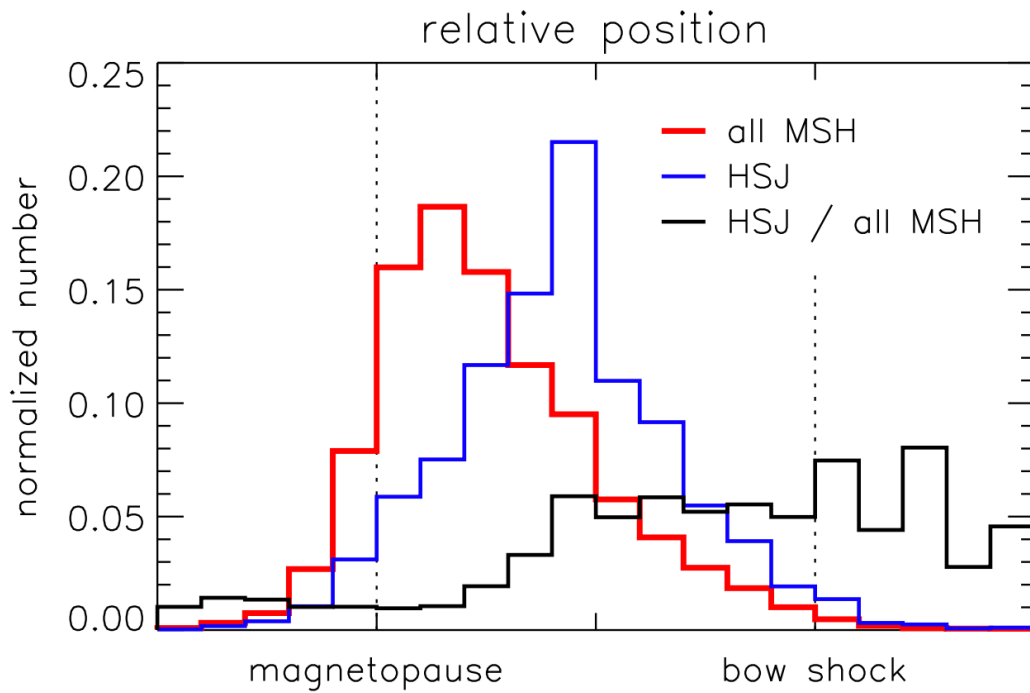
high  $M_A$ , on similar scales to Earth, making them good candidates for rippling. Even stronger shocks are seen at Jupiter and Saturn, though the IMF orientation at these distances is typically more oblique than in the inner heliosphere. The study of jets at planetary bow shocks and other shock environments is in its infancy, and will likely be an active area of interest in future.

### 1.4.3 Jet evolution and propagation

Compared to studies of jet formation, there have been relatively few studies on the evolution and propagation of jets through the magnetosheath. This is likely due, in no small part, to the difficulty in observing the evolution of a jet with single spacecraft observations.

Plaschke et al. (2013), in one of the first large statistical studies on jets, examined the typical observation locations of jets in the magnetosheath. Using empirical models for bow shock and magnetopause locations and taking into account biases arising from spacecraft orbits (more details in Chapter 2) they found that jets are most likely to be observed close to the bow shock, with observation probability dropping significantly closer to the magnetopause. This is shown by the black histogram in Figure 1.12. From this they inferred that most jets formed at the bow shock are unlikely to survive propagation to the magnetopause, that they are often dissipated, dispersed, or braked sufficiently that they are no longer detectable by selection algorithms. This idea has been supported by simulations such as those by Karimabadi et al. (2014) and Omidi et al. (2016) where jets have been seen to face instabilities and turbulence during their propagation.

Despite this, however, jets are still understood to impinge upon the magnetopause very often. Plaschke et al. (2016), used statistical models to estimate jet impact rates at the magnetopause as a function of cone angle and estimated jet perpendicular diameter. This was later expanded and refined by Vuorinen et al. (2019), and Plaschke et al. (2020c). They found that large, potentially geoeffective, jets with diameters of greater



**Figure 1.12:** Normalised histograms showing the occurrence of jets throughout the magnetosheath as observed by Plaschke et al. (2013). Red histogram shows the relative position of all magnetosheath observations used in their study, while the blue histogram shows the positions of measurements identified as jets. Black histogram shows the result of dividing the jet distribution by the magnetosheath distribution (and renormalising), creating a probability distribution for jet occurrence location. Taken from Plaschke et al. (2013).

than  $2 R_E$  impact the magnetopause over 9 times an hour during quasi-radial IMF, but less often with increasing cone angle. The smallest scales of jets were estimated to reach the magnetopause hundreds or thousands of times per hour.

Studies on the evolution of jet properties have been driven primarily by simulations. A recent work by Palmroth et al. (2021) combined jet observations from MMS with 2D global hybrid-Vlasov simulations to examine how jet properties evolve as they propagate towards the magnetopause. They found that jets thermalise with their surroundings with density, dynamic pressure, and magnetic field magnitude all falling from the bow shock to the magnetopause, while temperature rises, making near-magnetopause jets more akin to the surrounding plasma.

Dmitriev and Suvorova (2015) used multiple THEMIS spacecraft to track the evolution of a single jet and observed a decrease in overall speed, but an increase in the normal velocity component, suggesting it was focused towards the magnetopause. As they propagate into the magnetosheath, generally at higher velocities than their surroundings, jets can disturb the local plasma environment by driving bow waves and secondary particle accelerating shocks ahead of them (e.g., T. Z. Liu et al., 2020; Vuorinen et al., 2022b). It has been proposed through case studies (Plaschke et al., 2017) that during propagation, jets have the effect of aligning their magnetic fields with their velocity direction. Plaschke et al. (2020d) used MMS jet observations and superposed epoch analysis to confirm this in a statistical sense. They found that faster moving jets typically drive the alignment more strongly, but that the degree of alignment is largely unaffected by upstream solar wind conditions. They also noted that this is most prominent for jets observed close to the bow shock, and that the magnetic field typically relaxes back towards its original orientation as jets propagate towards the magnetopause. Recently, Goncharov et al. (2020) studied evolution and propagation using a data set of 1,400 jets seen by MMS. By comparing the observation location of jets across the magnetosheath they concluded that jets are able to propagate further into the magnetosheath for lower  $\theta_{Bn}$ , that is, downstream of the quasi-parallel shock.

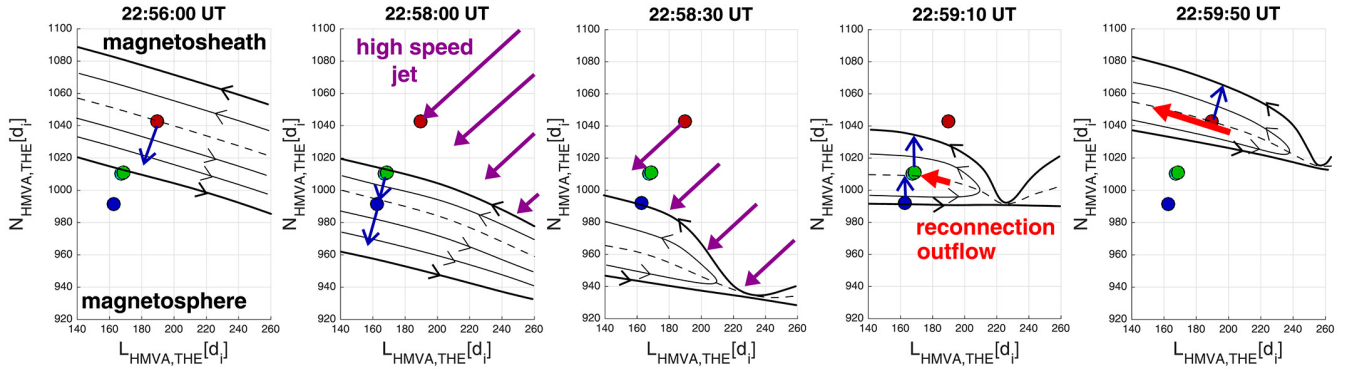
#### 1.4.4 Magnetospheric effects and role in magnetopause reconnection

As Earth-directed flows of mass and energy, jets couple solar wind, foreshock, and bow shock processes to the magnetopause and magnetosphere. In this respect, jets are an important topic to study in the context of magnetospheric dynamics and space weather. After impacting the magnetopause, jets have been seen to affect magnetospheric dynamics in several ways.

The primary identifying characteristic of jets is their significantly enhanced dynamic pressure. This pressure enables jets to significantly disturb the magnetopause upon impact. They can indent and rebound from the magnetopause surface (Escoubet et al., 2020; Amata et al., 2011; Dmitriev and Suvorova, 2015; Shue et al., 2009), launch propagating waves (Archer et al., 2014), or create surface eigenmodes, as was suggested by Plaschke et al. (2009) and recently observed by Archer et al. (2019). It has also been suggested (e.g., Gunell et al., 2012; Dmitriev and Suvorova, 2015) that jets may be able to ‘impulsively penetrate’ (Lemaire, 1977) the magnetopause, bringing denser magnetosheath plasma into the low density magnetosphere. They concluded that a jet’s penetrative ability was strongly linked to its velocity.

As discussed in Section 1.1.3, the onset of magnetic reconnection is understood to be controlled by the  $\beta$ -asymmetry, magnetic shear angle, and system scale size. Jets may be able to trigger or suppress magnetopause reconnection by changing the local plasma environment at the magnetopause with respect to these conditions. This was demonstrated in a study by Hietala et al. (2018), which utilised a time when the THEMIS probes were oriented in a string-of-pearls formation passing through the dayside magnetopause. Spacecraft entered the magnetosheath from the magnetosphere, and did not see reconnection occurring at the magnetopause, despite favourable conditions in terms of  $\beta$  and magnetic shear. They concluded that reconnection was prevented by the magnetopause layer being unusually thick. The spacecraft then saw a jet reaching the magnetopause. Shortly after, the magnetopause convected back over the spacecraft, and this time they observed a reconnection exhaust. It was determined that the large



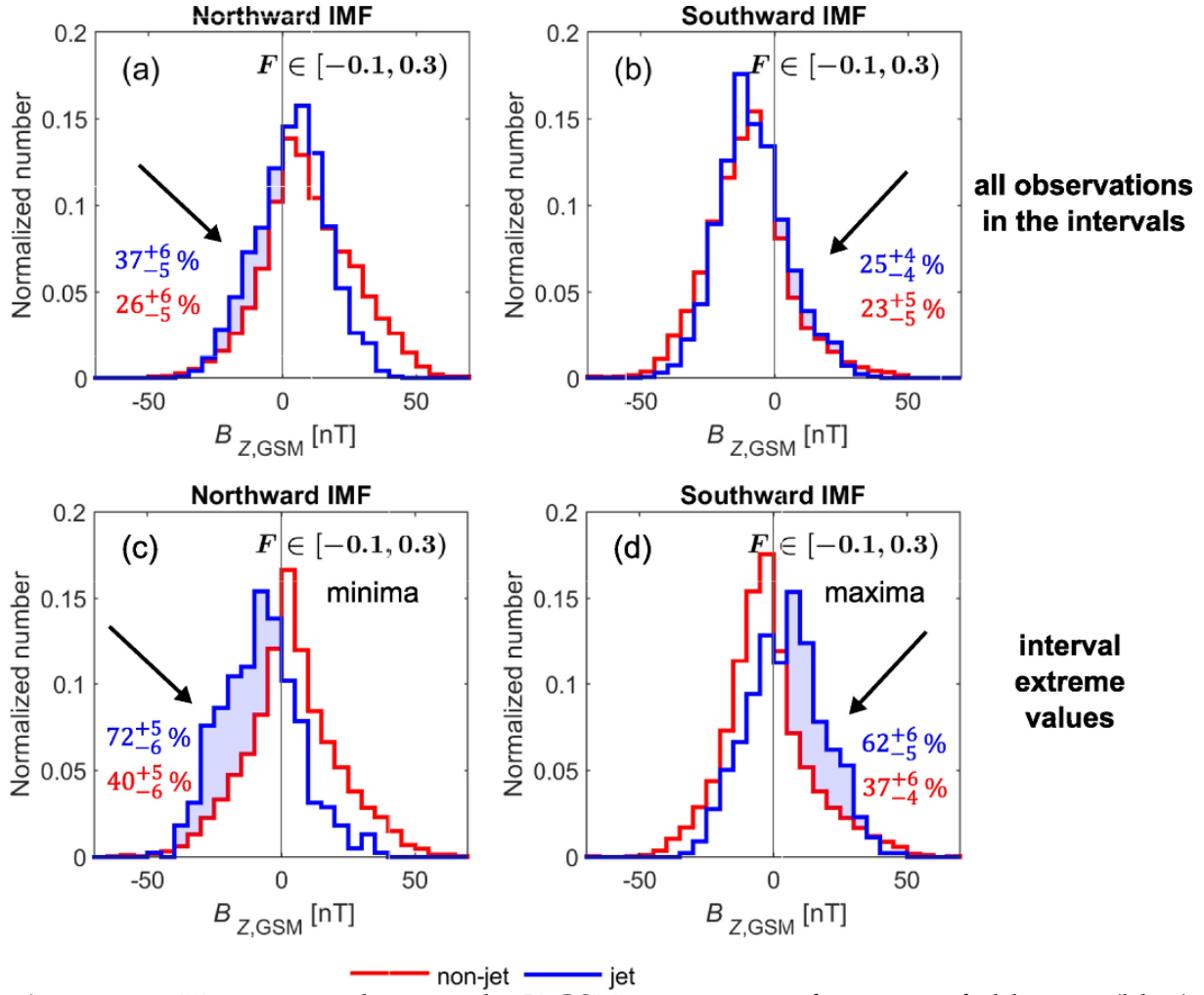


**Figure 1.13:** Schematic depicting how the high dynamic pressure of a jet was thought to compress the magnetopause layer, thus triggering reconnection at the magnetopause where there previously was none. Circles denote THEMIS spacecraft positions. Reproduced from Hietala et al. (2018).

dynamic pressure impulse exerted on the magnetopause by the jet was sufficient to compress the magnetopause current sheet so that it was able to reconnect. This process is illustrated in Figure 1.13. This study represents the only direct observation to date of a jet triggering reconnection at the magnetopause.

Other studies, however, have inferred jets triggering reconnection by connecting jet observations and ground effects. Nykyri et al. (2019) used a multi-spacecraft conjunction to deduce that jet-driven reconnection at the magnetopause contributed significant flux loading to the magnetotail and eventually led to the onset of a substorm. Most notably, this occurred during a period of weakly northward, quasi-radial IMF, i.e., a condition in which reconnection at the magnetopause would not traditionally be expected. Despite this, however, jets were observed in the magnetosheath containing pulses of strongly southward (negative)  $B_Z$  which, they inferred, provided the necessary antiparallel fields required for reconnection onset.

The idea that jets may be able to trigger reconnection during northward IMF was further investigated by Vuorinen et al. (2021). They conducted a statistical study of jets near the magnetopause and found that the strong southward pulses such as that seen by Nykyri et al. (2019) were found in around 13 % of jets. They saw that jets were significantly more likely to contain pulses of  $B_Z$  oppositely directed to the upstream IMF than non-jet magnetosheath intervals under similar solar wind conditions. This

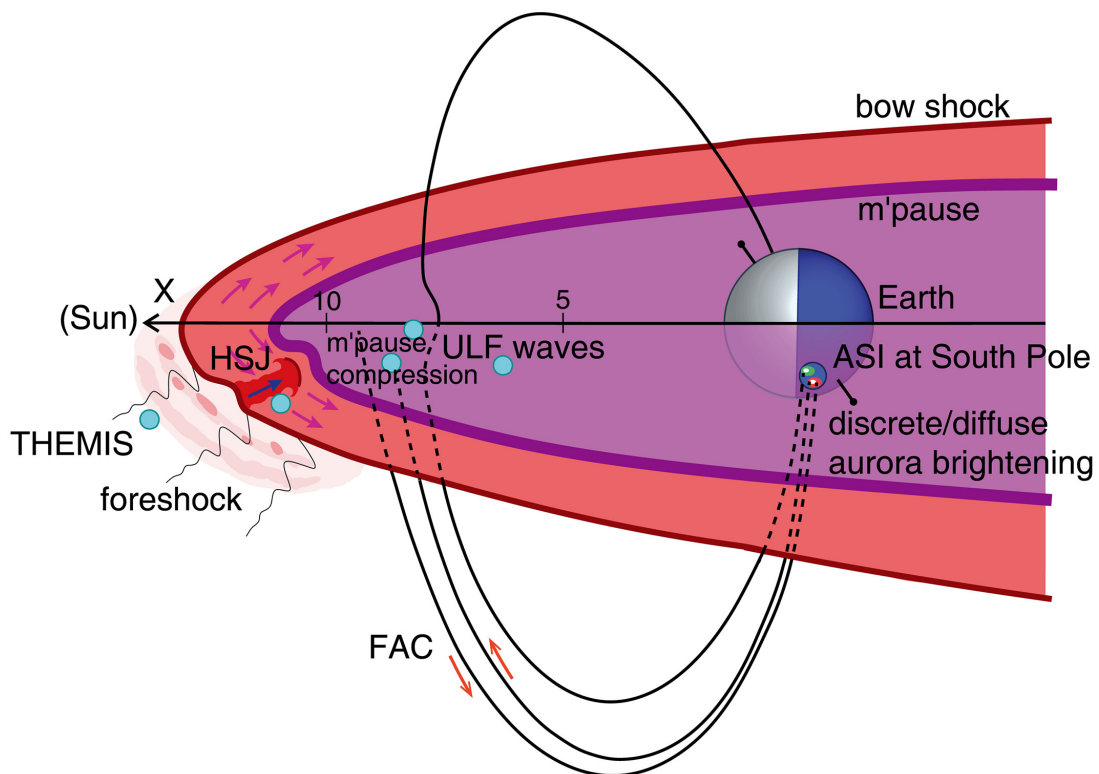


**Figure 1.14:** Histograms showing the Z-GSM component of magnetic field in jets (blue) versus non-jet magnetosheath intervals (red). Panels a) and b) use all plasma from within the intervals, while panels c) and d) use only the extreme points of each interval (the point most oppositely directed to the IMF  $B_Z$ ). Left column: northward IMF. Right column: Southward IMF. Reproduced from Vuorinen et al. (2021).

is shown in Figure 1.14, a key result of that study. When using all magnetic field data within jets they found that jets contain a marginally higher proportion of oppositely-directed  $B_Z$  than similar non-jet intervals (Figures 1.14a and b), but when examining the extreme portions of each interval, they saw that jets are significantly more likely to contain an opposite polarity pulse than the non-jet magnetosheath. From their statistics they were able to conclude that jets not only increase the likelihood of reconnection triggering during northward IMF, but also make it possible for jets to suppress ongoing reconnection during times of southward IMF. Their statistical results are discussed in more detail in Chapter 4.

The role of jets in magnetopause reconnection has also been explored in simulations. In the 2D global hybrid-kinetic simulations performed by Karimabadi et al. (2014) jets were seen to significantly disturb magnetosheath flow and drive bow waves ahead of them. The interaction of the bow waves and jets with the magnetopause caused strong perturbations on the surface, leading to the onset of reconnection and the formation of flux transfer events (FTEs). Later, Ng et al. (2021) analysed 3D hybrid simulations of the dayside magnetosheath during quasi-radial southward IMF (simulation run also studied by Omelchenko et al., 2021). They saw jets impacting the magnetopause and triggering bursty reconnection.

Recent studies have shed light on the ionospheric and ground effects of jets impacting the magnetopause. Multiple studies have investigated the link between jets and aurora. For example, Wang et al. (2018) studied how jet impacts contribute to the evolution of aurora. Using eight jets seen by THEMIS in the magnetosheath, they determined a causal relationship between impacts upon the magnetopause and discrete auroral brightenings, similar to those produced by the impact of interplanetary shocks, but on scales comparable to estimated jet diameters. Their inferred chain of events is depicted in Figure 1.15. In addition, dayside ‘throat’ auroras have been connected to magnetopause indentations, potentially arising from jet impacts during times of quasi-radial IMF (Han et al., 2016; Han et al., 2017; Han et al., 2018). Jets impacting the magnetopause have also been seen to produce periodic disturbances measured by ground-based magnetometers (Norenius et al., 2021; Wang et al., 2022).



**Figure 1.15:** Illustration depicting the process by which jets impacting the magnetopause are thought to produce auroral brightenings. Jets cause localised magnetopause compressions, which result in field aligned currents near the magnetopause. These go on to enhance electron precipitation and auroral brightening. Taken from Wang et al. (2018).

## 1.5 Research questions and thesis overview

Reflecting on the body of previous work, we identify key areas of study and formulate the following research questions, which we will address using in situ spacecraft observations. Each question corresponds to a chapter of this thesis.

### **1. What solar wind conditions are most favourable for jets to reach the magnetopause?**

Knowing that jets can be geoeffective (e.g., Hietala et al., 2018; Wang et al., 2018; Nykyri et al., 2019; Norenius et al., 2021), we would be interested in being able to forecast their effects. Space weather forecasting regimes typically rely on observations of the pristine solar wind at the L1 Lagrange point in order to predict the conditions arriving at the bow shock and the likely magnetospheric response. Therefore we want to know what solar wind conditions are most favourable for jets to form at the bow shock. Knowing, however, that not all jets make it to the magnetopause (Plaschke et al., 2013), predicting jet formation is not enough to confidently predict the rates of jet impacts on the magnetopause. We propose, therefore to separately determine the solar wind conditions that are most favourable for jets to resist dissipation and reach the magnetopause.

We will go on to show that the conditions for jet formation and propagation are not the same, with some solar wind parameters exerting oppositely directed influences on jet formation and propagation. Combining these, however, we see that jets are most likely to reach the magnetopause in high numbers during times of low IMF cone angle solar wind, high solar wind speeds, and low densities — all conditions typically associated with fast-type solar wind. This study is presented in Chapter 3.

### **2. What are the properties of jets near the magnetopause and how might they influence reconnection?**

Having established when jets are most likely to reach the magnetopause, we turn

our attention to their potential effects once there. To shed light on this, we first must understand the typical properties of jets at the magnetopause. By comparing these with the properties of jets seen forming at the bow shock we can begin to understand which types of jet are most likely to survive to the magnetopause, or how they may evolve during propagation. In terms of magnetospheric effects, we are particularly interested in the role of jets in reconnection. Several studies have shown that they may be able to trigger localised reconnection (Hietala et al., 2018; Nykyri et al., 2019), though we don't yet know how often we would expect this to occur. Vuorinen et al. (2021) showed that the magnetic field orientation within jets is statistically more likely to be favourable for reconnection than the non-jet magnetosheath during northward IMF, but also that jets may act to suppress reconnection during southward IMF. To view a more complete picture, however, we must consider other properties relevant to reconnection as set out in the  $\Delta\beta$ -shear condition (Swisdak et al., 2010; Phan et al., 2013).

By placing jets in the  $\beta$ -shear parameter space we will show that while jet plasma is generally unfavourable for reconnection, most jets at the magnetopause do satisfy the conditions necessary to modify reconnection from what would be expected based on the IMF orientation. This study is presented in Chapter 4.

### **3. How does the magnetopause respond to jet impacts?**

While various studies have seen or inferred jets triggering localised reconnection at the magnetopause (Hietala et al., 2018; Nykyri et al., 2019; Ng et al., 2021), the direct observational evidence is still very limited. We also note that it is possible that the role of jets in magnetopause reconnection may be overstated due to observational bias — i.e., studies are more likely to report cases of jets triggering reconnection than having no effect or suppressing it.

We therefore aim to probe the interaction of jets with the magnetopause in greater depth using a case study example, selected from the database by filtering for events likely to modify reconnection. In particular, we aim to test our findings on the  $\Delta\beta$ -shear

properties of jets and examine if their role in reconnection is well-predicted by these parameters and develop methodology to assess these complex and dynamic events. In doing so, we also probe the utility of the  $\Delta\beta$ -shear relation at the magnetopause, particularly for dynamic and impulsive inflow conditions such as those created by jets. We go on to conclude that in such environments the relation may not be a good predictor of reconnection favourability. This study is presented in Chapter 5.

We can visualise these research questions as surveying three regions of Earth's dayside magnetosphere, starting in the solar wind and moving Earthward in the chain of events leading to jets influencing magnetopause reconnection. This is illustrated by the numbering in Figure 1.9. Question 1 centres on the solar wind conditions arriving at the nose of the bow shock that are suitable for jet formation and propagation. Question 2 addresses the properties of jets within the magnetosheath and shortly in front of the magnetopause, making predictions for how they may influence reconnection. Finally, question 3 examines the magnetopause itself following jet impacts.

The remainder of this thesis is structured as follows: Chapter 2 introduces the data set used in our studies, as well as the spacecraft and instruments from which it is borne. We also introduce some key analysis and statistical techniques used in this thesis. Chapter 3 details our investigation of research question 1, regarding solar wind control of jet formation and propagation to the magnetopause. Chapter 4 examines research question 2, regarding jet properties and their likely influence on reconnection. Chapter 5 extends this with research question 3, using a case study to probe the magnetopause response to jet impacts. Finally, in Chapter 6 we summarise and discuss our findings, drawing conclusions and making suggestions for future work.

# Chapter 2

## Instrumentation, Data, and Methods

The work presented in this thesis is built on observations made by spacecraft around Earth's magnetosphere and in the solar wind. In this chapter we detail the provenance of these data, outlining the key spacecraft and instruments used. We also describe the process undertaken to form a database of jet observations, and describe some of the key methods and analysis tools used throughout.

### 2.1 Spacecraft and instruments

#### 2.1.1 THEMIS

The research presented in this thesis centres on observations made by the Time History of Events and Macroscale Interactions during Substorms spacecraft (THEMIS; Angelopoulos, 2008). It was launched on 17<sup>th</sup> February 2007 from Cape Canaveral, Florida (Figure 2.1) with the goal of shedding light on the processes behind substorm onset. The mission consists of five identical probes (denoted THA, THB, THC, THD, and THE, though some literature may refer to them as P5, P1, P2, P3, and P4, respectively), each with a suite of in situ instruments. The spacecraft are spin-stabilised, with a spin period of approximately 3 seconds.





**Figure 2.1:** The launch of THEMIS from Cape Canaveral, Florida, on 17<sup>th</sup> February 2007 on a Delta II rocket. Photo credit: NASA/Jerry Cannon.

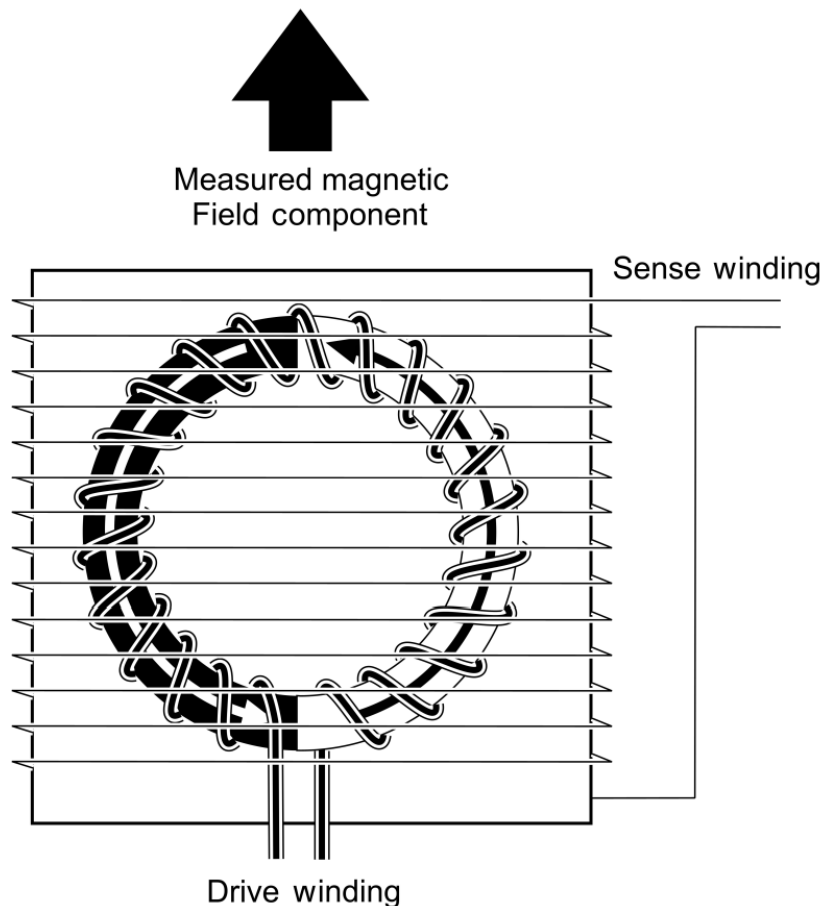
The orbits and apogees have been adjusted many times throughout the mission, allowing the spacecraft to survey different regions of space with variable separation and formation. In 2010, two of the probes (THB and THC) were re-positioned into a lunar orbit and re-branded as the Acceleration, Reconnection, Turbulence, and Electrodynamics of the Moon's Interaction with the Sun mission (ARTEMIS; Angelopoulos, 2011). This enabled them to investigate the magnetotail at a distance of around  $60 R_E$  downstream, and act as a near-Earth solar wind monitor when on the dayside. Though the primary goal of THEMIS centred on its nightside campaign, the extended mission has allowed for extensive coverage of the dayside magnetosphere. This is the area of focus in our studies. A core benefit of choosing THEMIS over other missions is the length of time for which it has been in operation. This allows us to compile a large data set with good coverage across the solar cycle and varying solar wind conditions and extremes. The spacecraft separation allows for simultaneous coverage of multiple magnetosheath regions, with identical probes and instrumentation, allowing for straightforward comparison.

In this thesis we predominantly make use of the THEMIS Fluxgate Magnetometer (FGM; Auster et al., 2008) and Electrostatic Analyser (ESA; McFadden et al., 2008) instruments. Here we briefly describe their function.

### 2.1.1.1 FGM

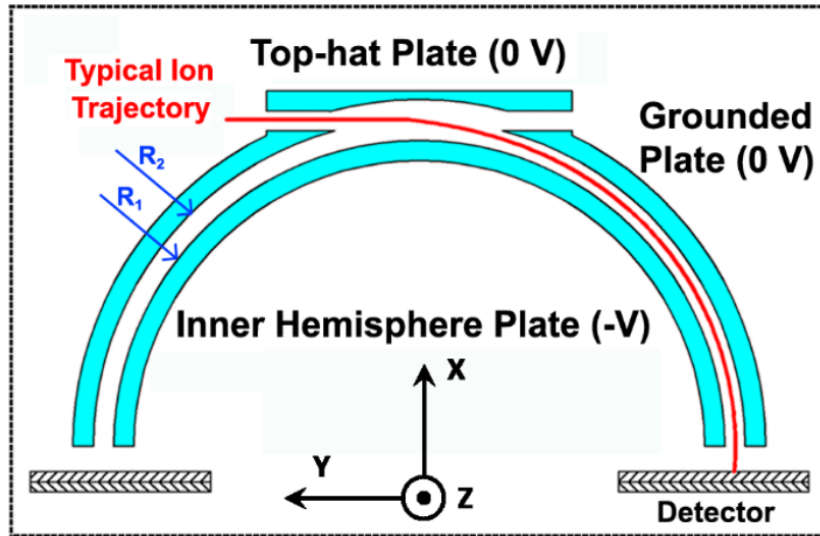
Magnetometers, instruments that measure magnetic fields, are amongst the most well-established and near-ubiquitous pieces of space hardware. Magnetometer sensors exist in several forms, though the most commonly used in space is the fluxgate. The Fluxgate Magnetometer (FGM; Auster et al., 2008) sensors on board each of the THEMIS probes sit on a boom, putting them 2 metres away from the main spacecraft body in an effort to maximise magnetic cleanliness and lessen the effect of the spacecraft and other instruments.

The main principles of the FGM are as follows. The sensors are comprised of three



**Figure 2.2:** Schematic of a single-axis fluxgate magnetometer. An alternating current is applied to the drive winding which is coiled around a ferromagnetic core. When an external field is applied, a voltage proportional to the field magnitude is induced in the sense winding. Taken from Miles et al. (2017).

key elements: a ferromagnetic core ring, a drive winding, and a sense winding. These are illustrated in Figure 2.2. The drive winding is coiled around the core and applied with an alternating current. Each half of the core (shaded black and white in Figure 2.2) generates a field with an oppositely directed component to the other half. With no external field, both halves of the core go in and out of magnetic saturation together, cancelling each other and inducing no current in the sense winding. However, if an external field is applied along the axis of the sensor, one side of the core reaches saturation faster, producing a net imbalance in flux, inducing a current in the sense winding. The magnitude of the induced voltage is proportional to the magnitude of the external field. By combining three cores in a tri-axial configuration, magnetic field vectors can be measured in three dimensions.



**Figure 2.3:** Schematic of a ‘top hat’ electrostatic analyser. A potential difference is applied across the parallel plates (blue), which only allows charged particles with a specific energy to charge ratio to enter the detector, where the particle count and entry angle is recorded. By sweeping the applied voltage and spinning the spacecraft (about the Y-axis), a 3D distribution function is recorded. Figure taken from Li et al. (2018).

### 2.1.1.2 Electrostatic Analyser (ESA)

Several types of space plasma instruments exist, though the type of interest here is the THEMIS Electrostatic Analyser (ESA; McFadden et al., 2008). There are two ESAs on board THEMIS, one which detects ions and one which detects electrons. They measure the distribution functions of particle populations, from which moments (density, velocity, and temperature) can be calculated. The type of instrument used on THEMIS is referred to as a ‘top hat’ electrostatic analyser, the main principles of which are as follows, and illustrated in Figure 2.3. An electric field is applied across two hemispherical parallel plates, which allow only particles with a specific energy per unit charge to enter the detector, recording the number of particles and direction of entry. By sweeping through a range of voltages, different particle energies can be detected, and a full 3D distribution built as the spacecraft spins, therefore providing plasma moments at a cadence of approximately 3 seconds.

### 2.1.2 OMNI database

Our understanding of the solar wind conditions near Earth is based primarily on spacecraft observations made at the L1 Lagrange point. This is approximately 1.5 million km (0.01 AU,  $\sim 235 R_E$ ) upstream of Earth. While measurements made at L1 are often representative of the conditions arriving at the magnetosphere within the broad context of the inner heliosphere, a significant amount of uncertainty still exists when using these measurements in magnetospheric studies. This is due to the lag time of approximately an hour during which solar wind structures may evolve, and also the fact that the measuring spacecraft can deviate by several tens of Earth radii from the Sun-Earth line. In an attempt to circumvent these issues, the OMNI database (King and Papitashvili, 2005) algorithmically propagates observations made at L1 such that they are more likely to represent those impinging on the bow shock nose.

To perform the time lagging, the algorithm considers the phase front normals of solar wind structures, the position of the observing spacecraft, and the location of the bow shock according to the Farris and Russell (1994) model. The database combines observations from a variety of L1 spacecraft, primarily Wind (Lepping et al., 1995) and ACE (Stone et al., 1998). Using coverage from these and other missions, the database provides near-continuous coverage spanning several decades, with data available at a variety of resolutions. For a full description of the algorithm and database, we refer the reader to the online documentation available at: [https://omniweb.gsfc.nasa.gov/html/omni\\_min\\_data.html](https://omniweb.gsfc.nasa.gov/html/omni_min_data.html). In our studies here we make use of the OMNI high-resolution data set, that is, measurements at a cadence of 1 minute.

## 2.2 Magnetosheath jet database

Throughout this thesis, we use a database of 13,096 jet observations derived from data from the five THEMIS spacecraft from 2008 to 2018 (inclusive). The data set was compiled algorithmically using methods developed by Plaschke et al. (2013). Some of these data are available in public repositories (Plaschke et al. (2020a) for 2008–2011, and

Plaschke et al. (2020b) for 2012–2018). Studies presented in this thesis represent the first usage of this full data set, though it should be noted that it contains the 2,859 jets first presented by Plaschke et al. (2013). Prior to the start of this project (October 2019), a list of THEMIS magnetosheath interval times and jet times, along with corresponding solar wind quantities from the OMNI database, were provided to me by a collaborator (F. Plaschke). These data are used directly in Chapter 3. Using the lists, I retrieved magnetosheath properties of whole jet intervals and non-jet times and time series data surrounding near-magnetopause jets using algorithms developed as part of the studies presented in Chapter 4 and Chapter 5.

The original description of the algorithmic selection process is given in Plaschke et al. (2013), but here we describe it in full and highlight the points most relevant to this work. Times when the THEMIS spacecraft were in the subsolar magnetosheath are selected as follows. All THEMIS data (from the ESA and FGM instruments at spin resolution) were interpolated such that all measurements share a common one second cadence. Each measurement by THEMIS is associated with upstream solar wind conditions taken from the OMNI database, averaged for the preceding five minutes and interpolated to the same cadence. In order to select an interval, the following quantities were required to be continuously available for at least two minutes: THEMIS ion velocity, temperature, density, energy flux, and magnetic field components, as well as OMNI magnetic field, ion velocity, density, and  $\beta$ .

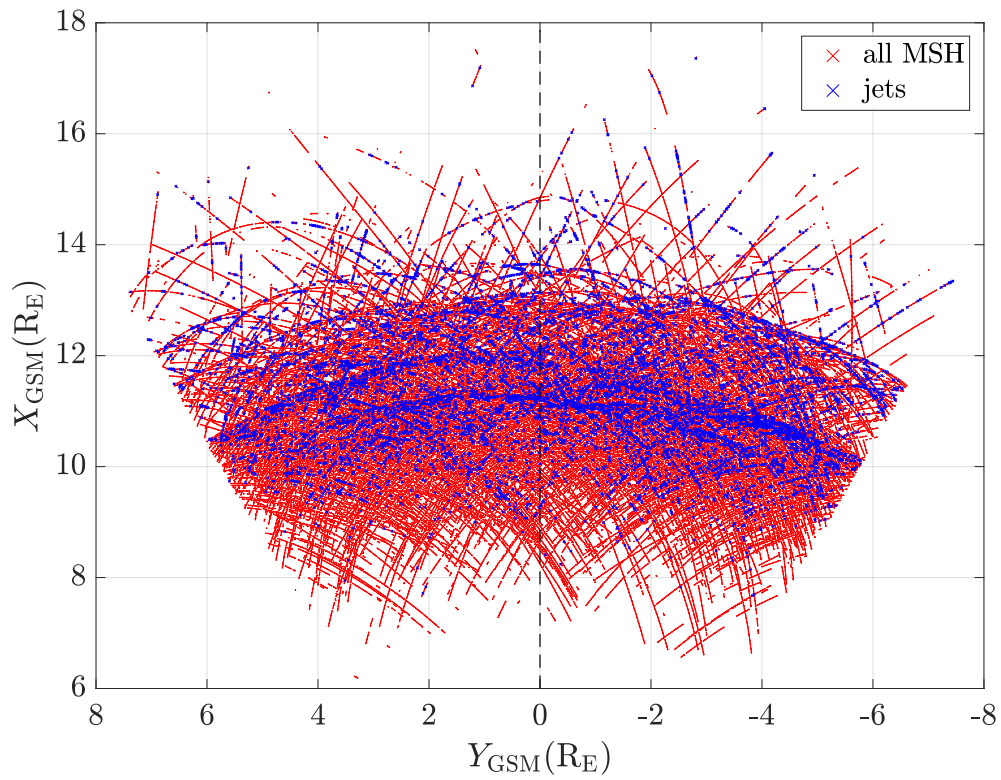
To define the subsolar magnetosheath, we restrict to observations made within a  $30^\circ$  cone with Earth at the tip, symmetrical about the Sun-Earth line, and between 7 and  $18 R_E$  radially from the centre of Earth. To ensure that only magnetosheath data were selected, it was required that the ion density must exceed twice that of the upstream solar wind and that the energy flux of 1 keV ions is greater than that of 10 keV ions. By requiring these conditions to be satisfied for at least two continuous minutes, we exclude partial boundary crossings and foreshock structures that typically have shorter timescales. This resulted in a data set of over 31 million (8,713.5 hours) magnetosheath

measurements spanning the 11 years.

Jets (such as in Figure 1.10) were selected from the magnetosheath intervals using several criteria. The most significant of these concerns the defining characteristic of a jet — its dynamic pressure. Jets are identified as instances where the  $X_{\text{GSE}}$ -directed dynamic pressure measured in the magnetosheath exceeds half that of the pristine solar wind, i.e., where Eq 1.11 is satisfied. A local maximum in the magnetosheath to solar wind dynamic pressure ratio is defined to be at time  $t_0$ , and a jet interval is defined to be all points either side of  $t_0$  where dynamic pressure remains above a quarter of the solar wind value.

To ensure that jets are directed Earthward, jets must have a negative (antisunward)  $V_X$  throughout the jet interval. This is of particular importance to the work presented in this thesis, as we aim to study the propagation of jets to the magnetopause. In order to facilitate the study of the plasma conditions before and after jets, Plaschke et al. (2013) mandated that each jet must have at least one minute of continuous magnetosheath data either side of the jet interval. To ensure that jets are localised velocity-driven dynamic pressure enhancements, we also require that these one minute intervals either side of the jet obey  $V_X > 0.5V_X(t_0)$  throughout, i.e., less strongly antisunward than the peak enhancement.

Applying this process for years 2008–2018 (inclusive) yielded a data set of 13,096 jets. Figure 2.4 shows the measurement locations of the magnetosheath intervals (red) and jets selected (blue) in the GSM X-Y plane. We can see that the vast majority of measurements were made between 9–13  $R_E$ , though magnetosheath observations span almost the full allowed range from 6.2–17.5  $R_E$ . This is indicative of the changing magnetopause and bow shock locations in response to variable solar wind dynamic pressure, with the outer and innermost measurements representing extreme conditions. It is also reflective of and biased by the typical spacecraft apogees. In the next section we will detail how we handle this non-uniform magnetosheath sampling to make meaningful comparisons of magnetosheath observations under different solar wind conditions.



**Figure 2.4:** Scatter plot showing locations in the GSM X-Y plane of magnetosheath observations (red) and jets (blue) in the subsolar magnetosheath. Jet observations shown are at  $t_0$ .



**Table 2.1:** Comparison of key statistics between data sets.

| Property                                | 2008–2011    | 2012–2018    | 2008–2018     |
|-----------------------------------------|--------------|--------------|---------------|
| Magnetosheath data (hours)              | 2,501.1      | 6,212.4      | 8,713.5       |
| Data outside model boundaries (hours)   | 283.5 (11 %) | 751.7 (12 %) | 1035.3 (12 %) |
| Number of jets                          | 2,859        | 10,237       | 13,096        |
| Number of jets outside model boundaries | 202 (7 %)    | 375 (4 %)    | 577 (4 %)     |
| Number of jets $F < 0.25$ (near MP)     | 678          | 1,256        | 1,924         |
| Number of jets $F > 0.75$ (near BS)     | 313          | 1,426        | 1,739         |

*Note.* Data from 2008–2011 were first introduced by Plaschke et al. (2013), while those from 2012–2018 are presented here for the first time. This study makes use of both data sets combined (last column). Magnetosheath boundaries are given by the empirical models of Shue et al. (1998) and Merka et al. (2005), and  $F$  is the fractional distance through this model magnetosheath, as described in Section 2.3.1.

As mentioned previously, this data set incorporates the data set first presented by Plaschke et al. (2013) (and used subsequently in other studies such as that by Vuorinen et al., 2019) which covered 2008–2011. The data from 2012–2018 had not previously been analysed, and we make use of the full 11 years combined. The work in this thesis, in particular in Chapter 3 (and published by LaMoury et al., 2021) represents the first usage of this full extended data set.

We extended the four-year database of Plaschke et al. (2013), covering only the solar minimum, to a full solar cycle for several reasons. An aim of this project is to make a step towards understanding and forecasting the space weather effects of jets. Naturally, space weather studies are generally concerned with extreme events and behaviour, with many effects showing some kind of solar cycle dependence. For example, from 2008 to 2011, only 12 % (292 hours) of magnetosheath data corresponded to upstream solar wind speeds of above  $500 \text{ km s}^{-1}$  with a maximum observed speed of  $736 \text{ km s}^{-1}$ , compared to 23 % (1433 hours) and a maximum of  $846 \text{ km s}^{-1}$  in the 2012–2018 data set, which contains the solar maximum. We give some comparative statistics for each data set in Table 2.1.

## 2.3 Methods and techniques

In this thesis we employ an array of statistical techniques in order to analyse spacecraft data. Specific methods are described in detail in the relevant chapters, but here we detail some of the more universal techniques employed throughout our studies.

### 2.3.1 Determination of bow shock and magnetopause locations

The variable dynamic pressure of the solar wind causes the magnetopause and bow shock positions to fluctuate, altering the thickness of the magnetosheath layer. In all three studies presented in this thesis, we wish to know the position of jet observations within the magnetosheath, specifically, whether they are close to the bow shock or magnetopause, without being able to directly observe the nearby boundary. Therefore, in order to make meaningful comparisons of single spacecraft observations in a dynamic magnetosheath, we place each observation on a normalised relative distance scale. Each magnetosheath observation is assigned with a value corresponding to its fractional distance through a one-dimensional model magnetosheath, where the boundary positions are calculated via empirical models using solar wind input conditions taken from OMNI. This fractional distance,  $F$ , is calculated by

$$F = \frac{R - R_{\text{MP}}}{R_{\text{BS}} - R_{\text{MP}}}, \quad (2.1)$$

where  $R$  is the radial distance of the spacecraft from Earth,  $R_{\text{MP}}$  the radial distance to a model magnetopause, and  $R_{\text{BS}}$  the radial distance to a model bow shock, such that  $F = 1$  at the bow shock and 0 at the magnetopause. This technique was first used to study jets by Archer and Horbury (2013). This is suitable for the subsolar region, where our observations were made, though may make for less meaningful comparisons further away from the Sun-Earth line. The jet detection algorithm would require a different approach at the flanks and at higher latitudes, where the overall magnetosheath flow is faster than in the subsolar region.

The models used for the magnetopause and bow shock are those by Shue et al. (1998) and Merka et al. (2005) respectively. Here we will briefly outline their key principles. The Shue et al. (1998) magnetopause model, which is itself a refinement of the Shue et al. (1997) model, is one of the most widely-used magnetopause models. It was developed via an analysis of a large database of magnetopause crossings seen by a variety of spacecraft and refined by specific analysis of extreme events. The empirical relation for the magnetopause depends on the dynamic pressure of the upstream solar wind as well as the IMF  $B_Z$ , both of which control the standoff distance and tail flaring angle. It is given by

$$R_{\text{MP}} = R_0 \left( \frac{2}{1 + \cos \theta} \right)^\alpha \quad (2.2)$$

where  $\theta$  is the solar zenith angle, given by  $\theta = \cos^{-1} (R_X/R)$  for measurement position vector  $\mathbf{R}$ .  $R_0$  is the the standoff distance at the subsolar point, and  $\alpha$  controls the degree of tail flaring, which can be open or closed. These two parameters are themselves given by

$$R_0 = (10.22 + 1.29 \tanh(0.184 (B_Z + 8.14))) P_{\text{dyn,SW}}^{-\frac{1}{6.6}}, \quad (2.3)$$

and

$$\alpha = (0.58 - 0.007 B_Z) (1 + 0.024 \ln (P_{\text{dyn,SW}})). \quad (2.4)$$

We apply an additional modification, which is to account for an aberration occurring as a result of the magnetosphere's lateral motion through the solar wind, which we take to be a constant  $30 \text{ km s}^{-1}$  (which can be calculated from orbital mechanics).

The Merka et al. (2005) bow shock model, which is itself a refinement of the Peredo et al. (1995) model, is an expression composed of many empirically-derived parameters. In the interest of brevity we do not give it in full here, instead referring the reader to the original publication. The primary controlling parameter is the Alfvén Mach number,  $M_A$ , and they determined that it performs well in the subsolar region for  $M_A = 5\text{--}20$ , exhibiting greater accuracy and stability than many other commonly-used models, such as that by Farris and Russell (1994).

Other models and methods of magnetosheath boundary determination exist. For example, a recent method developed by Sibeck et al. (2022) uses the magnetosheath velocity gradient and multi-point observations to estimate the bow shock and magnetopause standoff distances along the Sun-Earth line. Our choice of models is predominantly motivated by ease of comparison with previous authors. Specifically, the Merka et al. (2005) bow shock model and Shue et al. (1998) models are those used by Plaschke et al. (2013), which is a significant point of comparison for much of the work presented in this thesis.

Using these models, we are able to calculate a value of  $F$  for every measurement in the magnetosheath. Figure 2.5 shows the distribution of jet observation positions within this one-dimensional model magnetosheath. Figure 2.5a shows the 2,859 jets presented by Plaschke et al. (2013), Figure 2.5b shows the new data set containing 10,237 jets measured by THEMIS from 2012 to 2018 (inclusive), while Figure 2.5c shows these two data sets combined.

The red histograms show the location of all measurements made in the magnetosheath. We see this peak at  $0.1 < F < 0.2$ , indicating that the THEMIS probes spent more time near the magnetopause than near the bow shock. The blue histogram shows the observation locations of jets, selected from the magnetosheath intervals. From these we see that most jets were observed near the middle of the magnetosheath, at  $F \sim 0.5$ . The number of jets near the bow shock ( $F > 0.75$ ) and near the magnetopause ( $F < 0.25$ ) are given in Table 2.1.

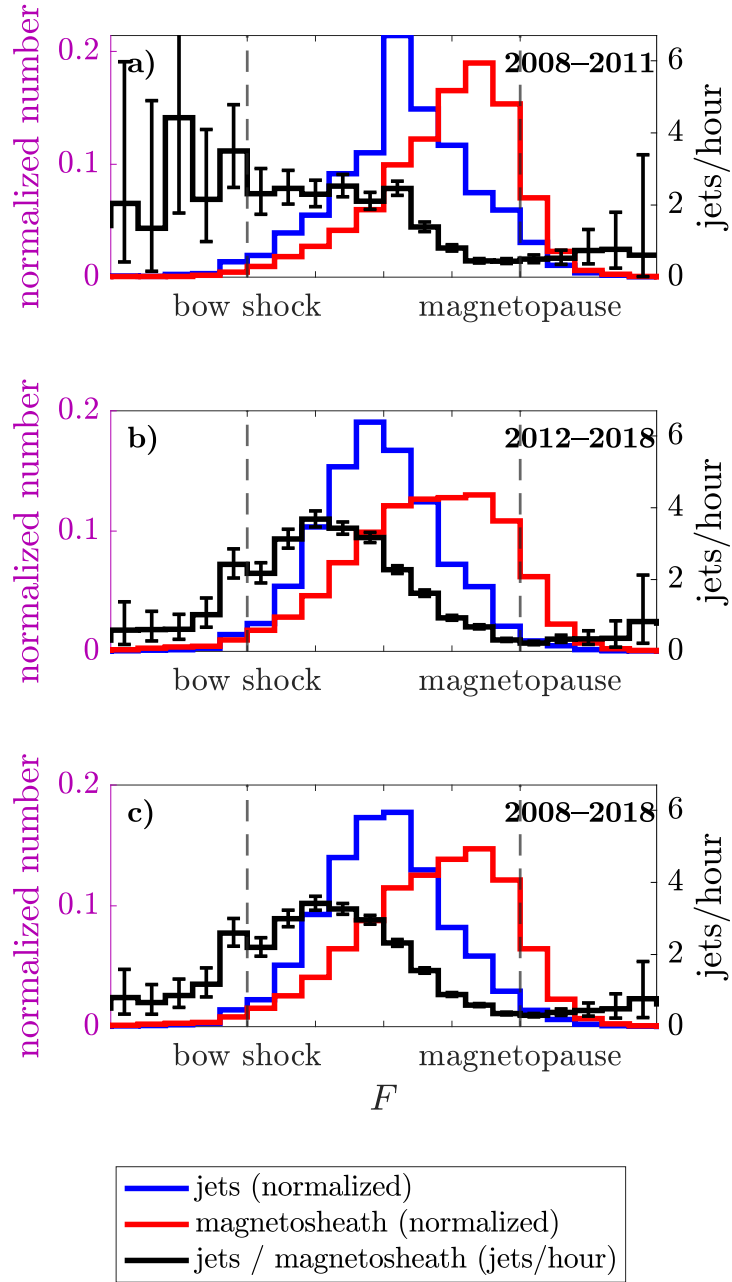
There is some amount of uncertainty regarding a jet's exact location with respect to the boundaries. As shown in Table 2.1, 12 % of time spent in the magnetosheath (red curves in Figure 2.5) and 4 % of jet observations (blue curves in Figure 2.5) are determined to be outside of our model boundaries despite the fact that the selection criteria are such that all data are determined to be from the magnetosheath. Though commonly used, the empirical models may have limitations. For example, Suvarova et al. (2010) suggested that, under prolonged periods of quasi-radial IMF, the magnetopause position may lie

significantly further out than what is predicted by the Shue et al. (1998) model, due to the foreshock being located directly upstream of the Earth and decreasing the pressure in the magnetosheath and on the magnetopause. In addition, Z.-Q. Liu et al. (2015) determined, with the use of MHD models, that the magnetopause location can deviate from the Shue et al. (1998) model when accounting for changing IMF orientations and the Earth's dipole tilt. To account for these uncertainties, we will keep our bin size coarse (e.g., one quarter of the model magnetosheath thickness) when filtering for specific magnetosheath regions. The models are driven by data from OMNI, which naturally contain some uncertainty as they are algorithmically propagated to the bow shock from measurements at L1. We do not consider this to be a significant issue, however, as any forecasting regime developed from our results would likely encounter the same limitations.

### **2.3.2 Removal of orbital biases and non-uniform sampling**

In order to make meaningful statements about jet observation probability, we must account for the non-uniform sampling of the magnetosheath as a result of spacecraft orbits and solar wind parameter variance. To do this in Figure 2.5, we divide each bin of the jet distribution by the corresponding bin of the magnetosheath distribution. This produces the black distribution, which is also scaled to units of jets observed per hour spent in the magnetosheath, per bin. Error bars are estimated using the Clopper-Pearson method to calculate a 95 % binomial confidence interval (see, e.g., Brown et al., 2001) as performed by the Matlab `binofit` function. In this system, the number of jet observations in a given bin are treated as a number of 'successes' out of a number of 'trials' given by the quantity of magnetosheath observations in the same bin. The confidence interval centres on the probability of success, and narrows with increasing number of trials, i.e., the larger the number of observations within a given bin, the smaller the error bars.

Throughout this thesis we will apply this technique of bias removal by normalising jet



**Figure 2.5:** Distributions of observation locations through model magnetosheath. Jet observations are shown in blue while the whole magnetosheath data set from which they are selected is shown in red. Both are normalised for ease of comparison and therefore correspond to the left y-axis. The black histograms give the probability distributions accounting for orbital effects, expressed in units of jets observed per hour spent in the magnetosheath at that  $F$ -range (right hand y-axis). a) THEMIS measurements from 2008–2011, as presented by Plaschke et al. (2013); b) new data set from 2012–2018; c) both data sets combined. Figure as shown in LaMoury et al. (2021).

observations by the non-jet magnetosheath in order to form probability distributions. This is effectively an application of Bayes' theorem for conditional probabilities, where we calculate the probability of a jet being observed, given a particular value of  $F$ . We can generalise this for any condition applied, such as a particular value of a solar wind parameter (e.g., speed or cone angle). In this context we can define that as

$$P(\text{jet}|\text{condition}) = \frac{P(\text{condition}|\text{jet})P(\text{jet})}{P(\text{condition})}, \quad (2.5)$$

where  $P(\text{condition}|\text{jet})$  is the fraction of jet observations that satisfy the condition, i.e.,  $N_{\text{jet}}(\text{condition})/N_{\text{jet}}$ .  $P(\text{jet})$ , the prior, is the probability of observing a jet with no conditions applied to the magnetosheath data set, i.e.,  $N_{\text{jet}}/N_{\text{msh}}$ . Finally,  $P(\text{condition})$  is the how often the condition is observed in the data set, i.e.,  $N_{\text{msh}}(\text{condition})/N_{\text{msh}}$ . Eq 2.5 then simplifies to

$$P(\text{jet}|\text{condition}) = \frac{N_{\text{jet}}(\text{condition})}{N_{\text{msh}}(\text{condition})}, \quad (2.6)$$

i.e., a simple division of the number of jet observations that satisfy a condition by the number of magnetosheath observations with the same condition. This is applied extensively in Chapter 3.

### 2.3.3 Minimum variance analysis

Space plasmas contain a large array of boundaries and discontinuities. In addition to the magnetospheric coordinate systems described in Section 1.2.4, it is sometimes useful to transform into a coordinate system that better represents and simplifies the geometry of the discontinuity. The technique commonly used to do this is known as minimum variance analysis (MVA). First used by Sonnerup and Cahill (1967) and detailed formally by Sonnerup and Scheible (1998), it has been used in a great many space plasma contexts such as CMEs, current sheets, and shock crossings. This powerful technique uses only single-spacecraft magnetic field measurements in order to find the normal direction of a plasma boundary layer. This is advantageous over other techniques as magnetometer data is usually available at higher time resolution than plasma instruments on most

spacecraft. In this thesis (in Chapter 5) we will use it to study reconnection at the Earth's magnetopause.

When crossing a current sheet, a spacecraft will see a rotation in magnetic field. The core principle of MVA is to find the spatial direction in which the field varies least, which is expected to be aligned with the current sheet normal,  $\mathbf{N}$ . This is as the normal component of the field is assumed to be constant across the boundary in order to ensure that the field is divergence free.

The normal vector is determined by finding the direction that minimises the quantity

$$\sigma^2 = \frac{1}{T} \sum_{i=1}^T \left| (\mathbf{B}_i - \langle \mathbf{B} \rangle) \cdot \hat{\mathbf{N}} \right|^2, \quad (2.7)$$

where  $\langle \mathbf{B} \rangle$  is the average magnetic field across total number of magnetic field vectors  $T$ . The three eigenvectors resulting from this process give the directions (in the original cartesian coordinate system, such as GSM) of the maximum, intermediate, and minimum variance axes in an orthogonal set. We term these the  $\mathbf{L}$ ,  $\mathbf{M}$ , and  $\mathbf{N}$  axes, respectively, and we can then perform a coordinate transformation to recast the data in this LMN coordinate system. For the method to be reliable, we require that the intermediate eigenvalue be much larger than the minimum eigenvalue. For a full mathematical description of the method, we refer the reader to Sonnerup and Scheible (1998).

We will use a slight modification of traditional MVA, known as hybrid-MVA (HMVA), which has been used in many more recent reconnection studies (e.g., Gosling and Phan, 2013; Mistry et al., 2017; Eastwood et al., 2018). In this system, the normal vector is determined using an alternative method to the above by considering the magnetic field vectors either side of the current sheet. It is calculated by

$$\hat{\mathbf{N}} = \frac{\mathbf{B}_1 \times \mathbf{B}_2}{|\mathbf{B}_1 \times \mathbf{B}_2|}, \quad (2.8)$$

where subscripts 1 and 2 refer to either side of the current sheet (which is the magne-



tosheath and magnetosphere in this context). This assumes that the inflow magnetic fields are parallel to the current sheet at their interface, making their cross product parallel to the normal.

The out-of-plane component is then given by

$$\hat{\mathbf{M}} = \hat{\mathbf{N}} \times \hat{\mathbf{L}}', \quad (2.9)$$

where  $\hat{\mathbf{L}}'$  is the unit vector direction of maximum variance determined using regular MVA. The direction of maximum variance in HMVA (which is the direction of reconnection exhaust) is given by

$$\hat{\mathbf{L}} = \hat{\mathbf{M}} \times \hat{\mathbf{N}}, \quad (2.10)$$

which completes the orthogonal set.  $\hat{\mathbf{L}}'$  and  $\hat{\mathbf{L}}$  are generally seen to exhibit good agreement.

## 2.4 Summary

In this chapter we have introduced the spacecraft, instruments, and data sets to be used throughout this thesis, those being the THEMIS mission and the OMNI database. We described how we used the data from these sources to form a database of subsolar magnetosheath intervals spanning 11 years, along with the corresponding upstream solar wind conditions. From these times we selected 13,096 jets via an algorithmic process. This forms the data set that will be used throughout the studies presented in the following chapters. We also described some of the key techniques and statistical methods applied in our studies. In the next chapter we use our database in full to assess the influence of the solar wind on jet formation and propagation to the magnetopause.

## Chapter 3

# The Dependence of Jet Formation and Propagation on Upstream Solar Wind Conditions

Material in this chapter has been published as:

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### 3.1 Introduction

Prior to the work presented here, there had been relatively little work on understanding what controls the number of jets reaching the magnetopause. In particular, no link had been made between rates of jet impacts at the magnetopause and the upstream solar wind conditions. Making this connection is necessary in order to be able to forecast the effects of jets on the magnetosphere. One suggestion was made by Goncharov et al. (2020), by simple comparison of observed jet distances from a model bow shock,

that jets propagate deeper into the magnetosheath downstream of the quasi-parallel shock than downstream of the quasi-perpendicular shock. In the subsolar region of the magnetosheath, where our observations lie, the quasi-parallel shock corresponds to low cone angle (the acute angle between the IMF and the Sun-Earth line) solar wind. This is now also a well-established favourable condition for jet formation, with only minor dependencies on other quantities such as solar wind speed, density, and IMF stability, noted by Plaschke et al. (2013) and Archer and Horbury (2013).

The focus of this chapter is, therefore, on determining what upstream solar wind conditions are most favourable for large numbers of jets to reach and impact the magnetopause, with a view to informing future forecasting regimes. In order to disentangle jet propagation from formation, we further break this problem down into two components: probability of jet formation at the bow shock, and probability of a given jet propagating all the way to the magnetopause. We consider these two processes separately, as it is not immediately obvious whether, for a given solar wind quantity, they would reinforce or counteract each other. We do indeed find that jet formation and propagation effects are independent, with some solar wind parameters producing oppositely directed effects. When combined, the net effect paints a picture of how different solar wind conditions affect the overall rate of jets reaching the magnetopause.

Jet occurrence as a function of solar wind conditions has previously been investigated, for example by Plaschke et al. (2013), though they did not limit to just those observed near the bow shock. We are able to do this using our 11 year jet data set, the largest of its kind at time of study. This allows us to reveal trends that were not previously apparent. We statistically determine the most favourable conditions for jet propagation to be those associated with the fast solar wind, with low IMF cone angle and high solar wind speed being the most strongly controlling properties. We see weak dependencies on IMF magnitude, Alfvén Mach number, and density, while plasma  $\beta$  and solar wind dynamic pressure have no net effect on the number of jets reaching the magnetopause.

## 3.2 Methods

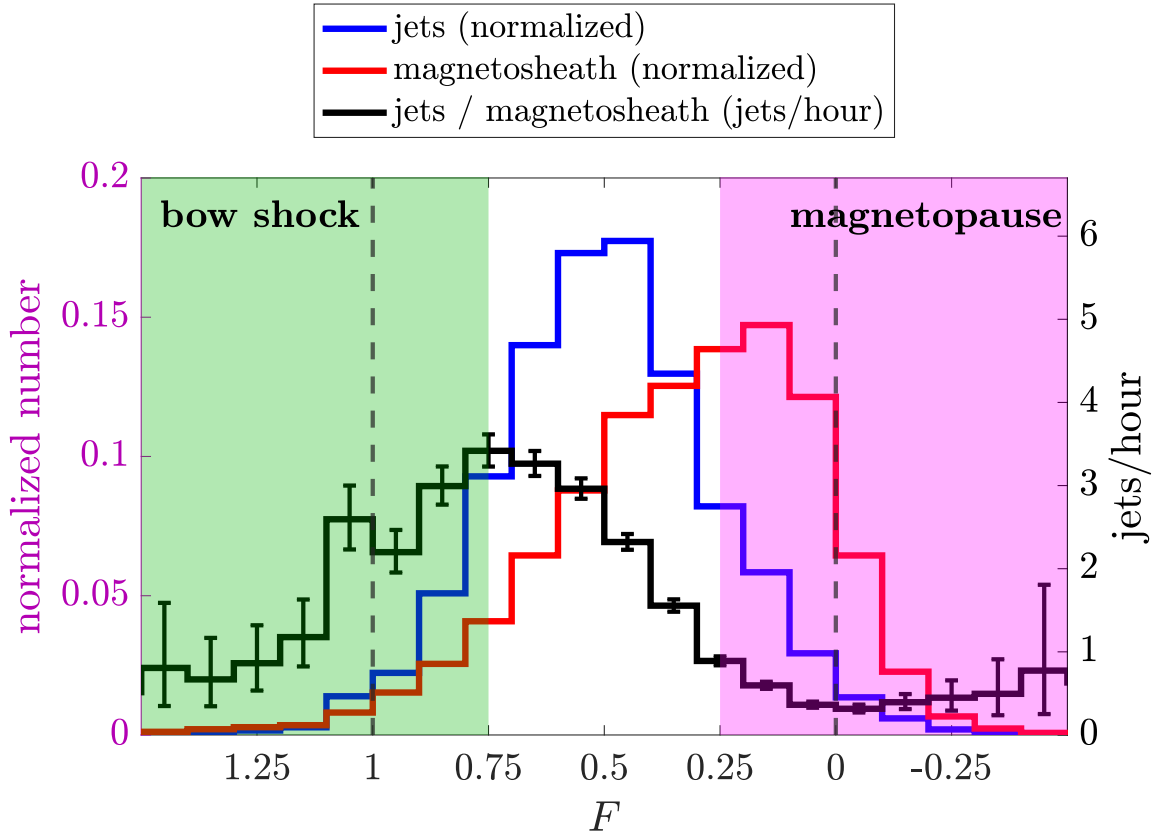
### 3.2.1 Data Set

The work presented in this chapter uses the whole data set of 13,096 jets compiled using the criteria described in Section 2.2, as well as the full range of data where THEMIS probes were determined to be in the subsolar magnetosheath from 2008–2018, along with associated upstream solar wind conditions as given by the OMNI database, averaged for the preceding five minutes. Note, however, that the analysis presented here considers only the solar wind conditions associated with the point of maximum magnetosheath to solar wind dynamic pressure ratio within each jet. The values at this moment (designated  $t_0$ ) are used to characterise each jet and its corresponding upstream solar wind conditions.

In the previous chapter we extended the data set of Plaschke et al. (2013) to show that the probability of jet observation falls from the bow shock to the magnetopause. We reproduce that analysis in Figure 3.1, where we show jet occurrence probability (in black) as a function of  $F$  for the whole data set. In order to understand what allows jets to reach the magnetopause, we subdivide our observations into regions of interest. We classify jets observed at  $F > 0.75$ , of which there are 1,739, as ‘near bow shock’ (green in Figure 3.1). Those seen at  $F < 0.25$ , of which there are 1,924, are classified as ‘near magnetopause’ (magenta). In this chapter, as well as later in Chapter 4, we will make extensive use of the jets seen in these regions, as they can be thought of as newly formed jets at the bow shock, and end-of-lifetime jets reaching the magnetopause, presenting opportunities to study their evolution and filtering through the magnetosheath.

### 3.2.2 Factors affecting jet formation

To understand what affects the probability of jet formation, we use the database to produce probability distributions showing the likelihood of observing a jet near the bow shock as a function of relevant solar wind parameters. As with Figure 3.1, we normalise



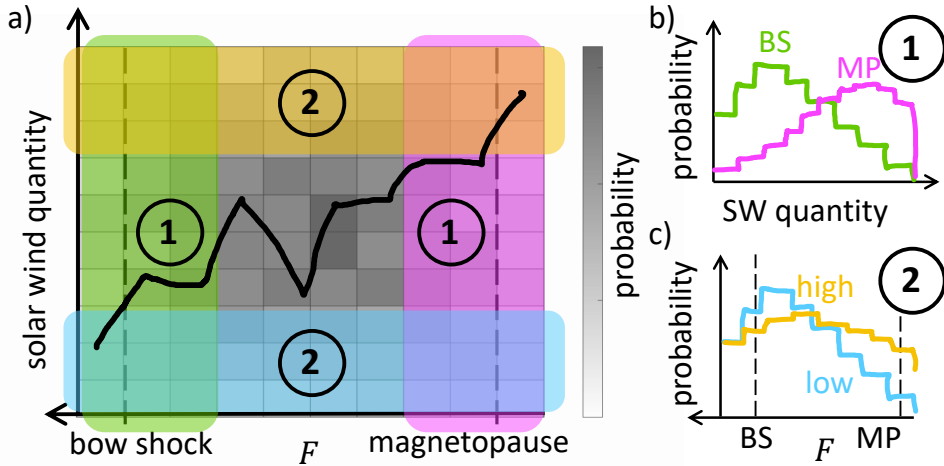
**Figure 3.1:** Distribution of THEMIS measurements expressed as a function of fractional distance,  $F$ , through the model magnetosheath. At the bow shock,  $F = 1$ , while  $F = 0$  at the magnetopause. The blue histogram shows the location of jet observations, while the red histogram shows the location of all magnetosheath samples from which jets were identified. The black distribution with error bars shows the result of dividing the jet histogram by the magnetosheath histogram, producing an effective probability distribution for jet occurrence, scaled in units of jets per hour. The green and magenta shaded regions denote the areas considered to be ‘near bow shock’ and ‘near magnetopause’, respectively.

jet distributions by the corresponding near-bow shock distribution for magnetosheath measurements. To account for non-uniform sampling of the parameter space, each bin of jet observations is therefore divided by the corresponding bin of the magnetosheath data set from which jets are selected, under the same conditions. The resulting distribution thus shows how likely a jet is to form under certain solar wind conditions, given that those conditions are observed. Note that a similar analysis was performed by Plaschke et al. (2013). A crucial difference between our study and previous works, however, is that we restrict our analysis to only jets and magnetosheath observations made near the bow shock (those with  $F > 0.75$ ) so that potential differences in jet propagation would not influence conclusions on factors affecting jet formation.

### 3.2.3 Factors affecting jet propagation

To be geoeffective, jets must interact with the magnetopause. It is therefore important to determine why some jets are able to travel further than others, and, with a particular view to forecasting, what solar wind conditions are favourable for jets propagating through the magnetosheath and reaching the magnetopause. We approach this problem via three analysis techniques, which are illustrated in Figure 3.2 where we show a cartoon of the parameter space to be explored. Method 1 involves considering the solar wind parameter distributions for jets near the bow shock and near the magnetopause, method 2 takes jets formed during high and low extremes of each solar wind quantity and compares their observation locations, and method 3 tracks the progression of the most likely solar wind conditions for jets as a function of observation location. We now introduce each of these methods in detail.

With single spacecraft observations of each jet, we cannot directly observe jets terminating or estimate their eventual propagation depth. The population of jets observed near the bow shock (the green region of Figure 3.2a) therefore contains jets that later went on to strike the magnetopause as well as those that dissipated shortly downstream of the shock. We can infer the conditions most favourable for jets to reach the magnetopause,



**Figure 3.2:** a) Cartoon of the parameter space explored to determine how solar wind conditions affect jet propagation. In method 1 (panel b), normalised probability distributions of solar wind quantities are compared for near-bow shock (green region) and near-magnetopause (magenta) jets. In method 2 (panel c), normalised probability distributions in  $F$  are compared for high (orange) and low (cyan) values of each solar wind quantity. The bold line in panel a illustrates method 3, where the evolution of the maximum probability solar wind parameter bin is tracked across the full  $F$  range.

however, by isolating the population of jets observed shortly in front of it. If jet propagation depth is dependent on a particular solar wind parameter, we would expect to see a change in the distribution of this parameter corresponding to jet observations at different depths into the magnetosheath (different values of  $F$ ). Our first method for establishing how the solar wind conditions affect jet propagation is, therefore, to compare the solar wind parameter probability distributions for newly formed jets close to bow shock ( $F > 0.75$ ), with jets observed reaching the magnetopause ( $F < 0.25$ ). Differences between the two distributions (Figure 3.2b) may indicate that the solar wind quantity in question has an influence on the ability of a jet to propagate to the magnetopause.

The second approach (Figure 3.2c) taken is to compare relative distance ( $F$ ) distributions (as in Figure 3.1) filtered by extreme values of each solar wind parameter. These can be interpreted as the orange and cyan regions in Figure 3.2a. Threshold values are set at the 85<sup>th</sup> and 15<sup>th</sup> percentiles of the magnetosheath distribution for each solar wind parameter, thus corresponding to ‘high’ and ‘low’ regimes. As jet occurrence falls from the bow shock to the magnetopause, we expect most distributions to broadly follow

this trend. A difference in gradient between the two distributions, however, implies that a solar wind quantity may influence expected jet propagation depth. If a particular solar wind condition is highly favourable for jet survival, we expect its distribution to be flatter. In both this and the previous method we use the normalisation technique described previously, so that the resulting plots are probability distributions.

The third technique used to investigate jet propagation takes into account the underlying probability distribution to determine how the average solar wind value varies for jets observed across the magnetosheath. This is illustrated by the black line in Figure 3.2a which traces the progression of the maximum probability bin for each vertical slice of constant  $F$ . This allows us to assess if jet penetration depth has a clear dependence throughout the magnetosheath on the controlling factors previously identified. It is important to bear in mind that the plasma parameter values shown at a given point in the magnetosheath are not those measured at that location, but instead correspond to the upstream solar wind conditions that formed a jet measured at that location.

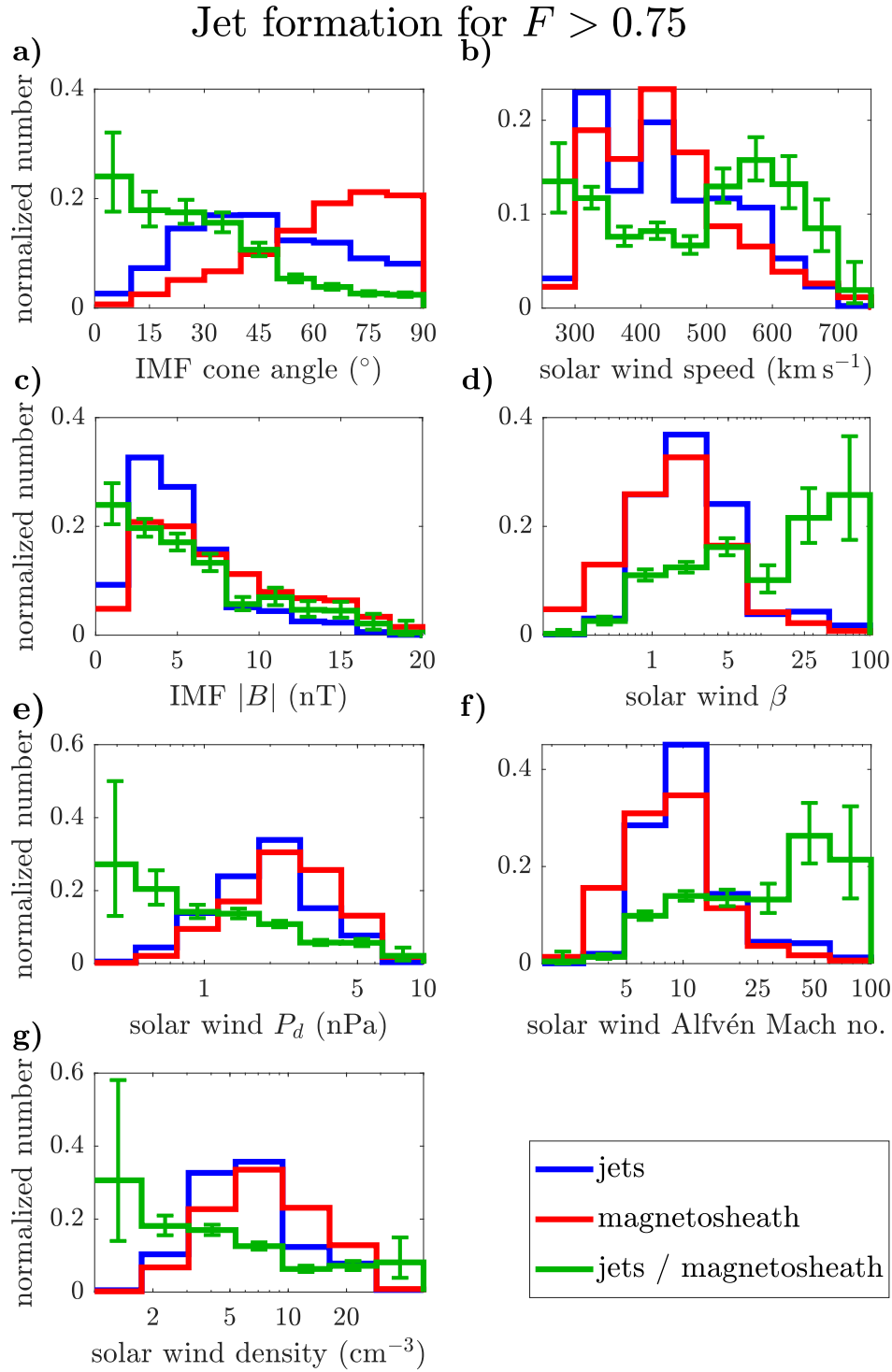
## 3.3 Results

### 3.3.1 Jet formation

Figure 3.3 shows probability distributions for jet formation at the bow shock as a function of each solar wind parameter studied. As in Figure 3.1, blue histograms represent raw jet observations and red histograms are the distributions for the whole magnetosheath data set from which jets are selected. Green histograms (those with error bars) show the probability distributions produced by dividing the jet samples by the corresponding magnetosheath data. The error bars are calculated using the methods described in Section 2.3.2, i.e., by calculating a 95 % binomial confidence interval for the probability of observing a number of jets from magnetosheath intervals during the same conditions.

From the green curve in Figure 3.3a, we see that jet formation is highest during low





**Figure 3.3:** Distributions of upstream solar wind conditions, illustrating how they affect the probability of jets forming at the bow shock. Observations associated with jets are shown in blue, the whole magnetosheath data set in red, and the normalised probability distributions for jet formation (those with error bars) in green. All observations are restricted to  $F > 0.75$ , i.e., near the bow shock, corresponding to the green region of Figure 3.2. Solar wind quantities shown are: a) IMF cone angle; b) solar wind speed; c) IMF magnitude; d) solar wind plasma  $\beta$  (log scale); e) solar wind dynamic pressure (log scale); f) solar wind Alfvén Mach number (log scale); g) solar wind density (log scale). Figure as presented in LaMoury et al. (2021).

IMF cone angle solar wind. This is in agreement with the findings of Plaschke et al. (2013) who, with their smaller data set, concluded that cone angle was the only strongly controlling factor, but noted weak dependencies on density and wind speed. Low IMF  $|B|$  (Figure 3.3c), high  $\beta$  (Figure 3.3d), low dynamic pressure (Figure 3.3e), and high Alfvén Mach number (Figure 3.3f), also appear to promote jet formation. From Figure 3.3g it does indeed appear that jets are more likely to form during low density wind, arguably displaying a more than minor dependence. The results for Alfvén Mach number and  $\beta$  are in agreement with the conclusions of Goncharov et al. (2020), though they found the opposite result for the IMF magnitude. It should be noted, however, that their data set was significantly smaller (1,400 jets across the whole magnetosheath) than this present study, and they did not distinguish between formation and propagation effects.

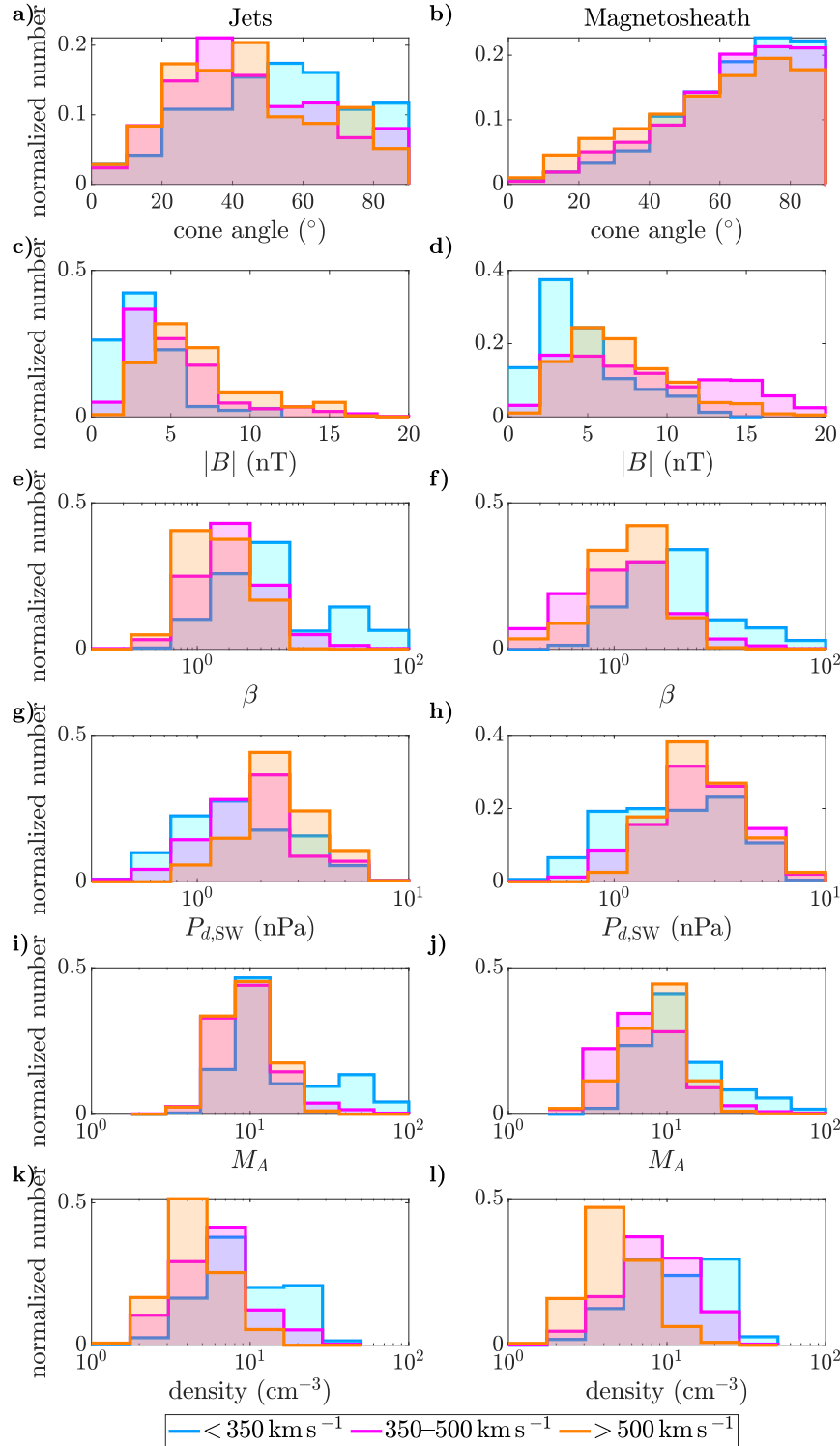
The dimensionless parameters of  $\beta$  and Alfvén Mach number are composed of other quantities under study (see Section 1.1.1), and we can see their dependence on those quantities. Given that jet formation appears to be most likely during low density solar wind, we would expect the most favourable condition to be low  $\beta$ , on account of the linear dependence. This is not what we observe, however. The reason for this is the inverse square dependence of  $\beta$  on magnetic field magnitude. Jets are most likely to form during low IMF  $|B|$ , i.e., high  $\beta$ , and it is this that dominates in the compound parameter. Similarly, the Alfvén Mach number depends on the square root of density, varies linearly with solar wind speed, and inversely with magnetic field strength and it is once again this that dominates the observed trend. In addition, the compound parameter of dynamic pressure is composed of both density and speed, with a squared dependence of speed. The resulting distribution most resembles that of density, however, perhaps due to the non-monotonic solar wind speed distribution.

In the green curve of Figure 3.3b we see a somewhat peculiar bimodal signature for jet occurrence probability as a function of solar wind speed. Occurrence probability initially declines with increasing speed, reaching a low plateau at 350–500 km s<sup>-1</sup>, before

increasing to a peak at around  $600 \text{ km s}^{-1}$ , with diminishing probabilities upwards of this point. It is notable as the only solar wind parameter investigated that does not produce an approximately monotonic trend in jet occurrence probability. A similar dip in jet occurrence for mid-range solar wind speeds was observed by Archer and Horbury (2013), in particular for jets downstream of the quasiparallel shock.

To investigate the cause of this signature, we examined the interdependence of different solar wind parameters. In particular, we studied the dependence of each parameter on solar wind speed. Figure 3.4 shows sets of histograms for each solar wind parameter studied, displayed separately for data associated with jets and the general magnetosheath. In each, we split the data by corresponding solar wind speed in line with the different regions of the green curve in Figure 3.3b. The cyan histograms correspond to the first declining region for speeds below  $350 \text{ km s}^{-1}$  (454 jets), the orange histograms corresponds to the high peak and second declining phase, for speeds greater than  $500 \text{ km s}^{-1}$  (525 jets), and the magenta histograms correspond to the dip region for speeds of  $350\text{--}500 \text{ km s}^{-1}$  (760 jets).

The majority of panels show expected behaviour. For example, in both the jet and magnetosheath distributions, density scales inversely with solar wind speed (Figures 3.4k and 3.4l). This is consistent with our understanding of fast-type solar wind emerging from coronal holes being less dense than the slow-type wind formed from closed field lines. Most other properties studied show a similar monotonic dependence across the three categories. An exception, however, can be seen in Figure 3.4d, which shows IMF magnitude for all times THEMIS probes were in the magnetosheath. Here we see the magenta histogram representing solar wind speeds of  $350\text{--}500 \text{ km s}^{-1}$  shifted to the right of the other two distributions. The implication of this is that in our data we find higher than average IMF magnitudes during times of mid-range solar wind speeds. Indeed, within the dataset we find that large ( $> 10 \text{ nT}$ ) values of IMF magnitude occur most often at solar wind speeds of around  $400 \text{ km s}^{-1}$ . The corresponding trends can also be seen for related quantities  $\beta$  and the Alfvén Mach number.

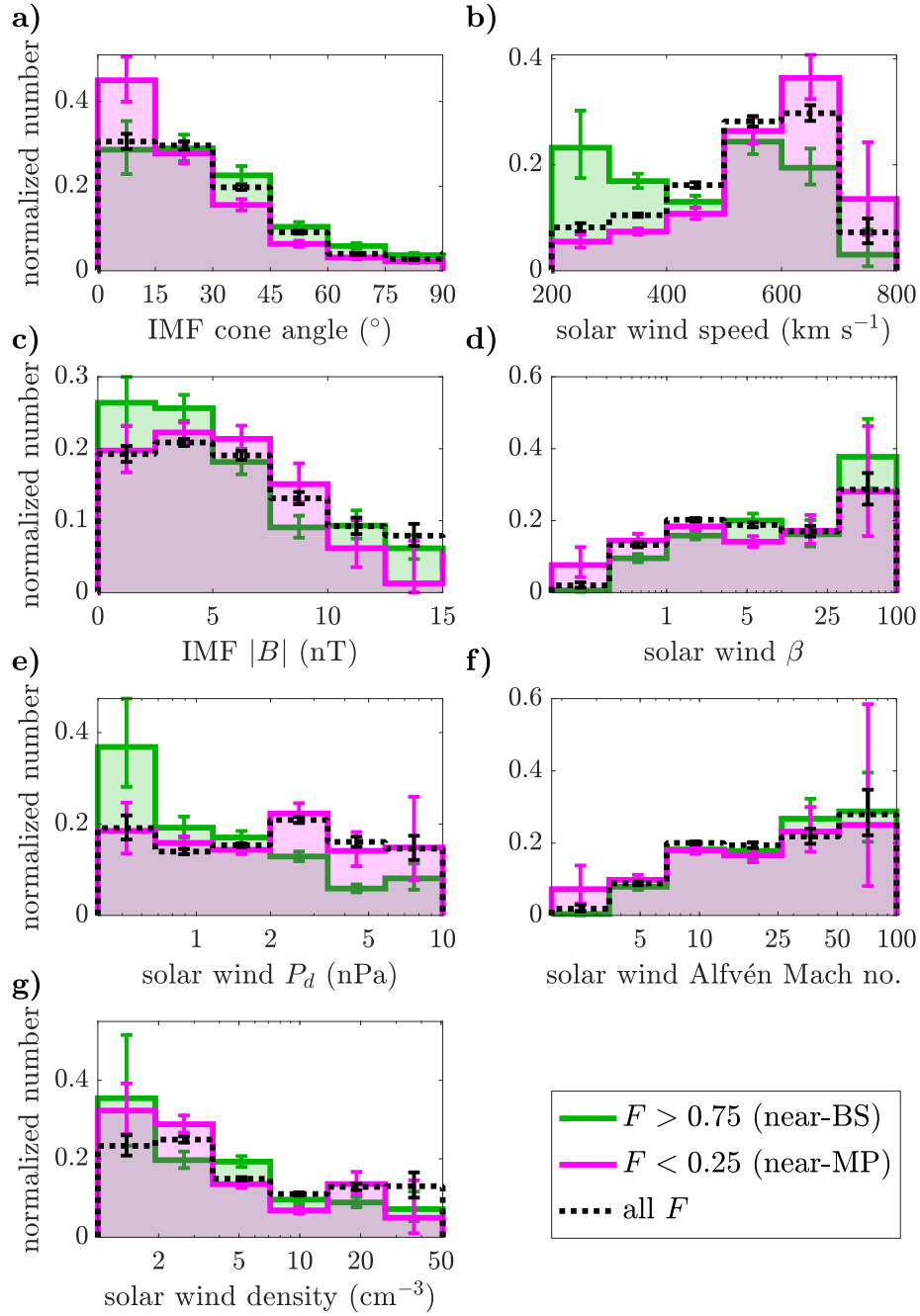


**Figure 3.4:** Histograms showing the distribution of each solar wind parameter investigated, separated by different values of solar wind speed. Plots in the left column show solar wind conditions during jet observations, while the right column shows distributions for all times that THEMIS probes were in the magnetosheath. In each, the cyan histogram shows data with wind speeds of less than 350 km s $^{-1}$ , the magenta histograms show data associated with wind speeds of 350–500 km s $^{-1}$  (the dip region in Figure 3.3b), and orange histograms show data associated with solar wind speeds above 500 km s $^{-1}$ . a-b) IMF cone angle; c-d) IMF magnitude; e-f) solar wind plasma  $\beta$  (log scale); g-h) solar wind dynamic pressure (log scale); i-j) solar wind Alfvén Mach number (log scale); k-l) solar wind density (log scale).

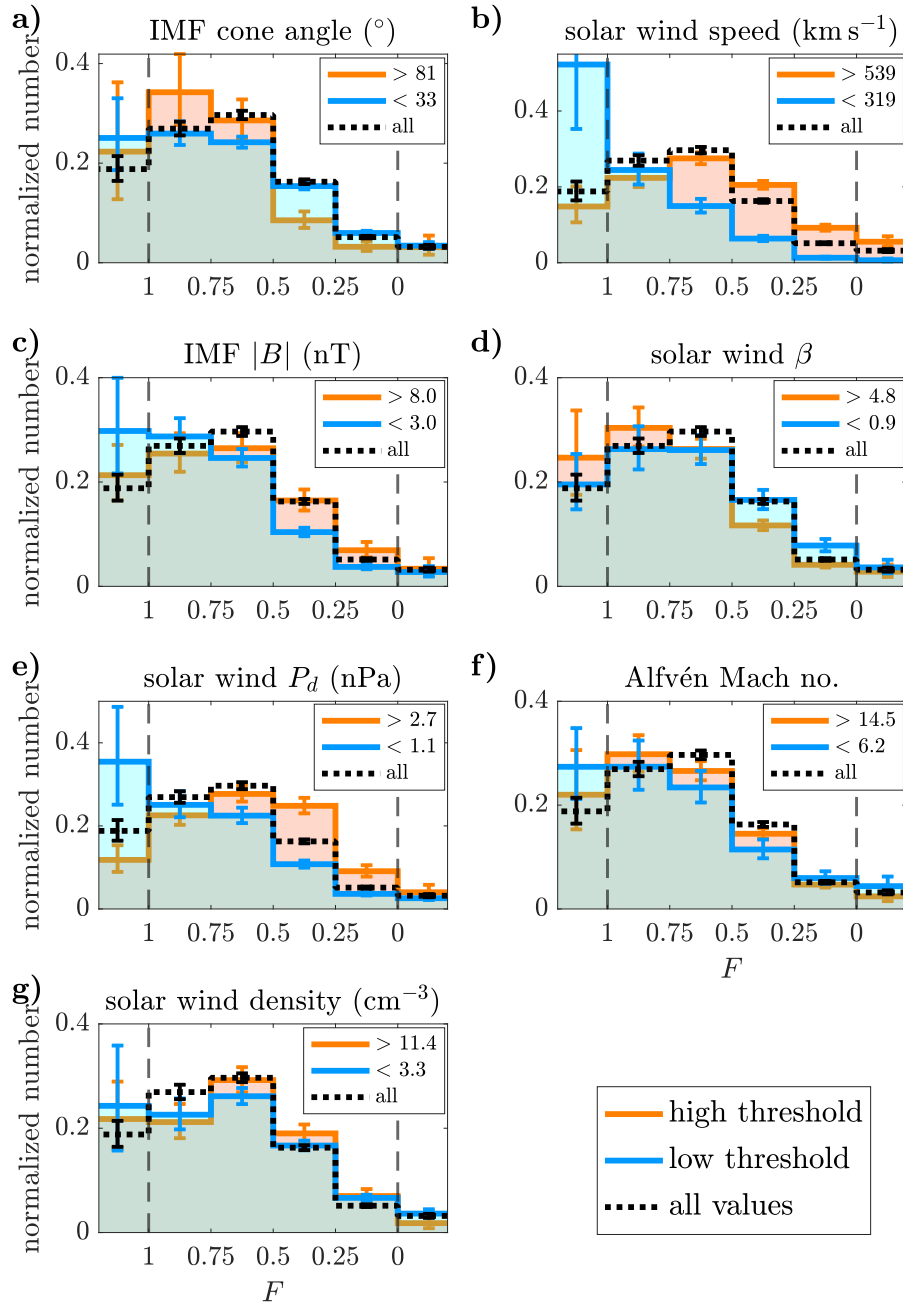
As established from our analysis of jet formation conditions and in particular Figure 3.3c, we know that high magnetic field strengths appear to hinder the formation of jets at the bow shock. Therefore we believe that it is this interdependence between solar wind speed and IMF magnitude that modulates the jet formation probability distribution for solar wind speed, producing the dip in the middle region.

### 3.3.2 Jet propagation

Figure 3.5 shows the results of the first technique (Figure 3.2b) used to determine the effect of solar wind conditions on jet propagation. The overlaid histograms show the distributions of solar wind parameters for jets observed close to the magnetopause ( $F < 0.25$ , magenta) of which there are 1,924, compared with jets observed near the bow shock ( $F > 0.75$ , green) of which there are 1,739. The colours indicate correspondence with the green and magenta regions of Figure 3.2a. IMF cone angle (Figure 3.5a) appears to be a controlling factor for jet propagation, with jets observed near the magnetopause showing an even stronger preference to occur during low cone angles than near-bow shock jets. Solar wind speed (Figure 3.5b) shows a very clear split, with jets observed near the bow shock recording far slower upstream solar wind speeds than jets near the magnetopause, implying that jets formed during faster wind will be more likely to reach the magnetopause. The distributions in Figures 3.5c, 3.5d, 3.5f, and 3.5g, representing IMF magnitude, plasma  $\beta$ , Alfvén Mach number, and density, respectively, lie roughly on top of each other, overlapping in their error bars and showing no clear skew. This suggests that, within uncertainty, they have no effect on jet propagation. Figure 3.5e, showing solar wind dynamic pressure, indicates that jets observed near the bow shock are generally formed of low dynamic pressure solar wind while jets at the magnetopause are formed from a range of dynamic pressures. This creates a separation in the upper region of the scale, suggesting that high dynamic pressure solar wind creates jets more likely to reach the magnetopause. This is compatible with the clear dependence on solar wind speed.



**Figure 3.5:** Distributions of upstream solar wind properties for jets, separated by near-bow shock ( $F > 0.75$ , green) and near-magnetopause ( $F < 0.25$ , magenta) jets. Distribution for all  $F$  values shown with a black dotted line. a) IMF cone angle; b) solar wind speed; c) IMF magnitude; d) solar wind plasma  $\beta$  (log scale); e) solar wind dynamic pressure (log scale); f) solar wind Alfvén Mach number (log scale); g) solar wind density (log scale). Figure as presented in LaMoury et al. (2021).



**Figure 3.6:** Normalised distributions of jet observation locations in model magnetosheath, separated by high and low threshold values (the 85<sup>th</sup> and 15<sup>th</sup> percentiles) of upstream solar wind parameters. In each, orange histograms are for jets observed with solar wind conditions above a high threshold, while cyan distributions represent those below a low threshold. Unconstrained distributions are shown with a black dotted line. a) IMF cone angle; b) solar wind speed; c) IMF magnitude; d) solar wind plasma  $\beta$ ; e) solar wind dynamic pressure; f) solar wind Alfvén Mach number; g) solar wind density. Figure as presented in LaMoury et al. (2021).

Figure 3.6 shows the results of our second technique, that is, jet  $F$  distributions of jets separated by high and low values (the 85<sup>th</sup> and 15<sup>th</sup> percentiles) of each solar wind parameter (as in Figure 3.2c). In each panel, orange histograms show high solar wind values, while cyan regions show low values, where the colours once again correspond to the regions highlighted in Figure 3.2a. The potential factors identified to enhance jet propagation via the previous method once again show confirmation of their influence, with the two distributions showing clear separation. These are low IMF cone angle (Figure 3.6a), high solar wind speed (Figure 3.6b), and high dynamic pressure (Figure 3.6e). Figure 3.6a provides a broader statistical backing for the assertion made by Goncharov et al. (2020) that jets propagate further into the magnetosheath downstream of the quasi-parallel shock. In addition, Figures 3.6c and 3.6d suggest that, according to this analysis technique, higher IMF  $|B|$  and low solar wind  $\beta$  may in fact promote jet propagation. These factors did not produce a noticeable effect via the first technique. The Alfvén Mach number and solar wind density (Figures 3.6f and 3.6g) do not show a clear effect.

The results of our third technique are shown in Figure 3.7. These are sets of 2D histograms, three panels for each solar wind quantity studied. Each shows the fraction of observations made at a particular magnetosheath location during a corresponding solar wind condition. The top panels (blue) represent the jet observations, the middle panels (red) show the background magnetosheath observations, and the bottom panels (purple) show the jet distribution normalised by magnetosheath data to eliminate orbital biases, analogous to the blue, red, and black histograms respectively in Figure 3.1. On each, the dotted line traces the progression of the median solar wind quantity for each slice of constant  $F$ , while the solid line traces the maximum value bin in each slice.

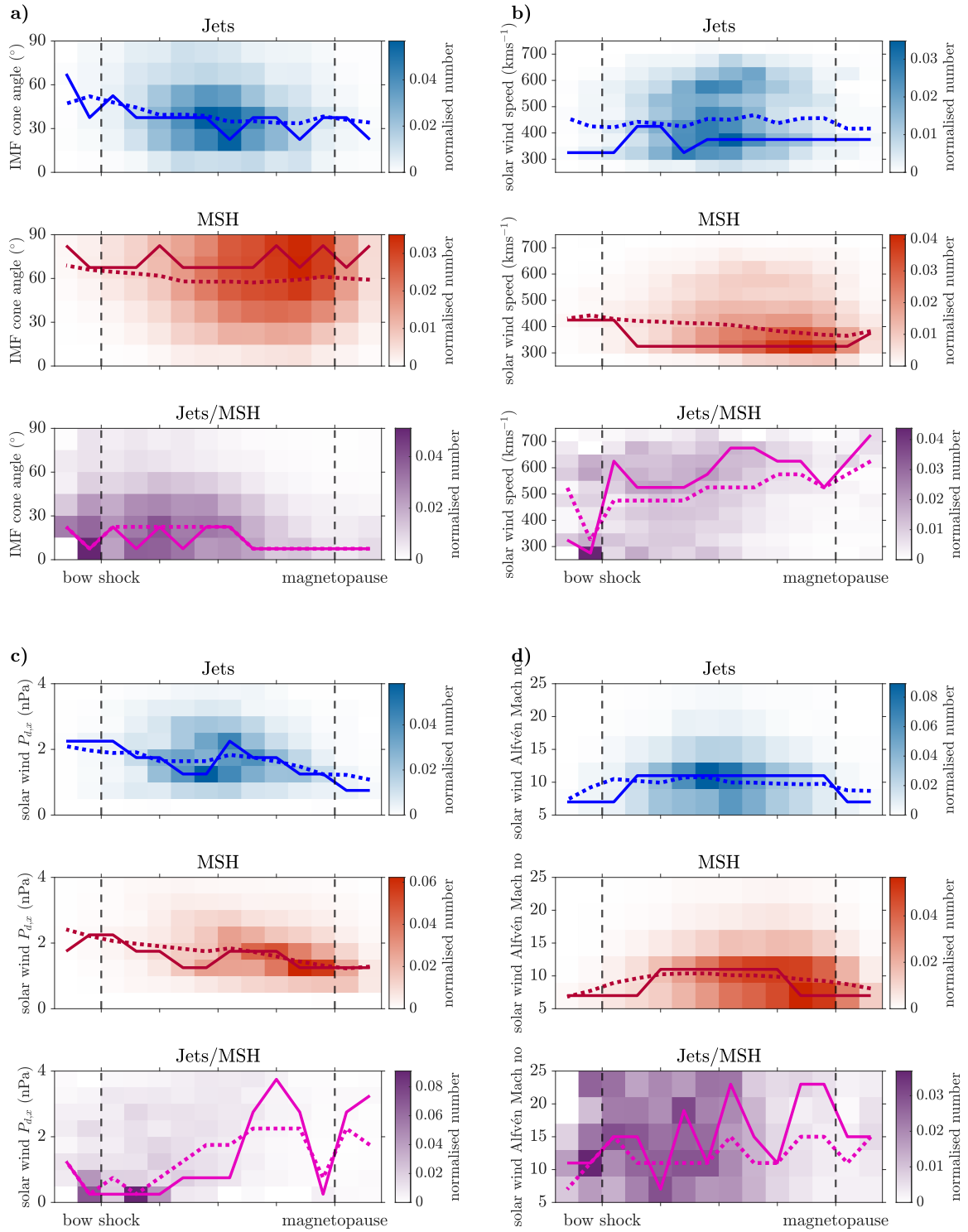
The bottom panel of Figure 3.7a appears to show that lower cone angles are to be expected for jets moving through the magnetosheath, though the progression of the median and maximum traces is somewhat limited due to the overall very strong pref-



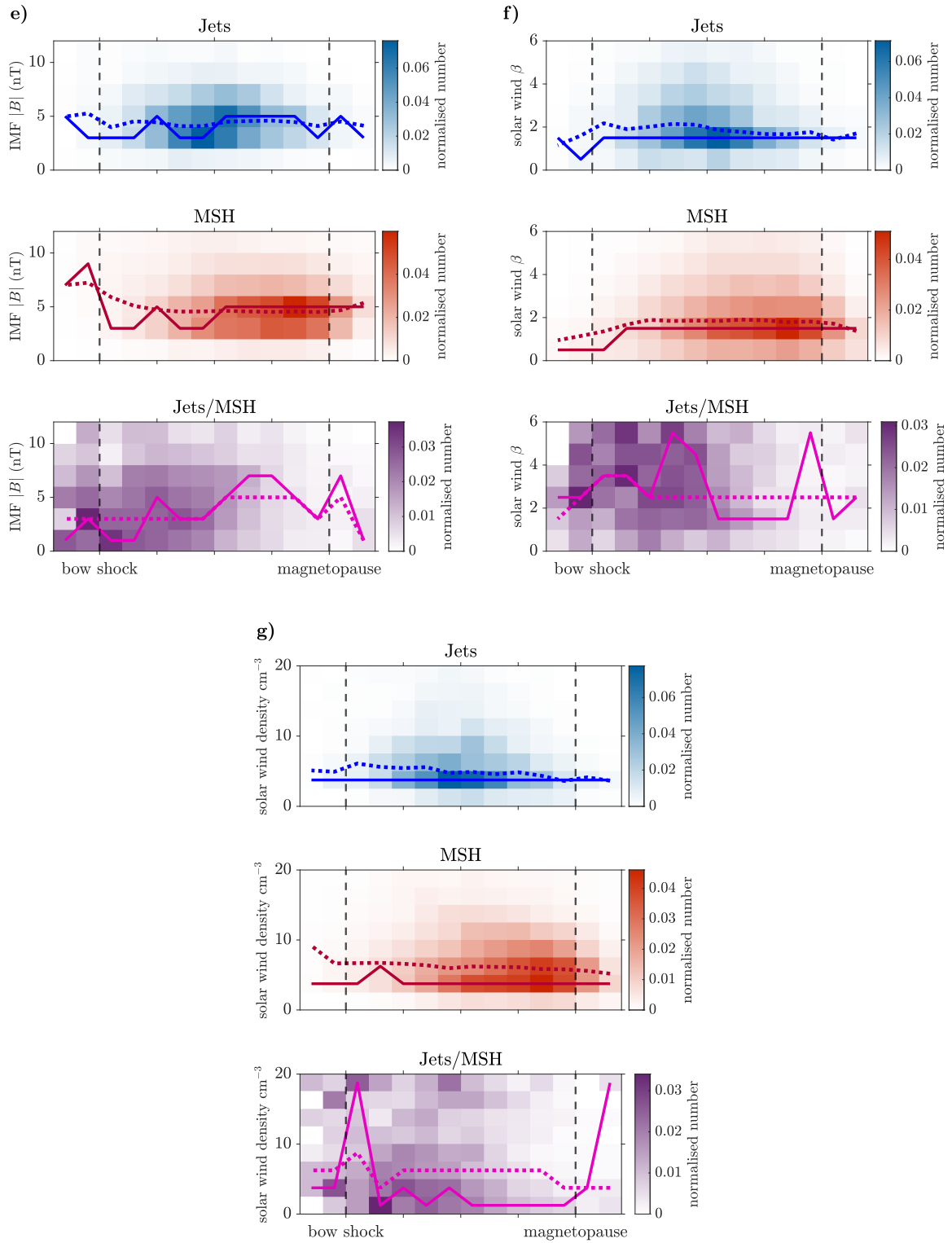
erence for low cone angles. What is very clear, however, is the white space in the top right corner, indicating that jets of high cone angle wind seldom make it to the magnetopause. Solar wind speed (Figure 3.7b) shows a relatively smooth variation across the magnetosheath, with jets near the bow shock being generally formed of slower wind than those at the magnetopause. The same can be said of solar wind dynamic pressure (Figure 3.7c). Alfvén Mach number (3.7d) displays more variability but can be seen to increase closer to the magnetopause, which was not observed by the other methodologies. The IMF magnitude (3.7e) appears to peak for jets observed close to the magnetopause, which was also seen in Figure 3.6. Solar wind  $\beta$  (3.7f) and density (3.7g) appear to have no perceptible trend with  $F$ .

### 3.3.3 Combining formation and propagation effects

Thus far we have considered the solar wind control of jet formation and jet propagation separately. For example, we have seen that a low IMF magnitude is favourable for the creation of jets (Figure 3.3c), but also that a higher IMF magnitude increases the likelihood of a jet surviving from the bow shock to the magnetopause (Figure 3.6c). On first glance, these two statements may seem contradictory but it is in fact possible for a solar wind parameter to affect jet formation and propagation differently and independently. However, with regard to the number of jets reaching the magnetopause, our results so far give us no information as to the relative magnitudes of these effects. In order to determine which regime might dominate, we present Figure 3.8 which, like Figure 3.6, shows  $F$  distributions separated by high and low values of each solar wind parameter, taken at the 85<sup>th</sup> and 15<sup>th</sup> percentile thresholds. The key difference here is that, instead of simply normalising, we express histograms in units of jets observed per hour the spacecraft spent in the magnetosheath, within each  $F$  bin, under those solar wind conditions. This combines both formation and propagation effects, enabling us to extract the rates of jets reaching the magnetopause under different solar wind conditions. The dashed black curves show the  $F$  distributions unconstrained by solar wind conditions and are therefore representative of the black curve in Figure 3.1



**Figure 3.7:** Probability density maps for observing jets formed during particular solar wind conditions at different positions in the magnetosheath. Blue: jet observations, red: magnetosheath intervals, purple: the quotient of blue and red. For each slice of constant  $F$ , dotted lines trace the progression of the median, while solid lines trace the maximum value bin. a) IMF cone angle; b) solar wind speed; c) dynamic pressure; d) Alfvén Mach number. (Continued on next page).

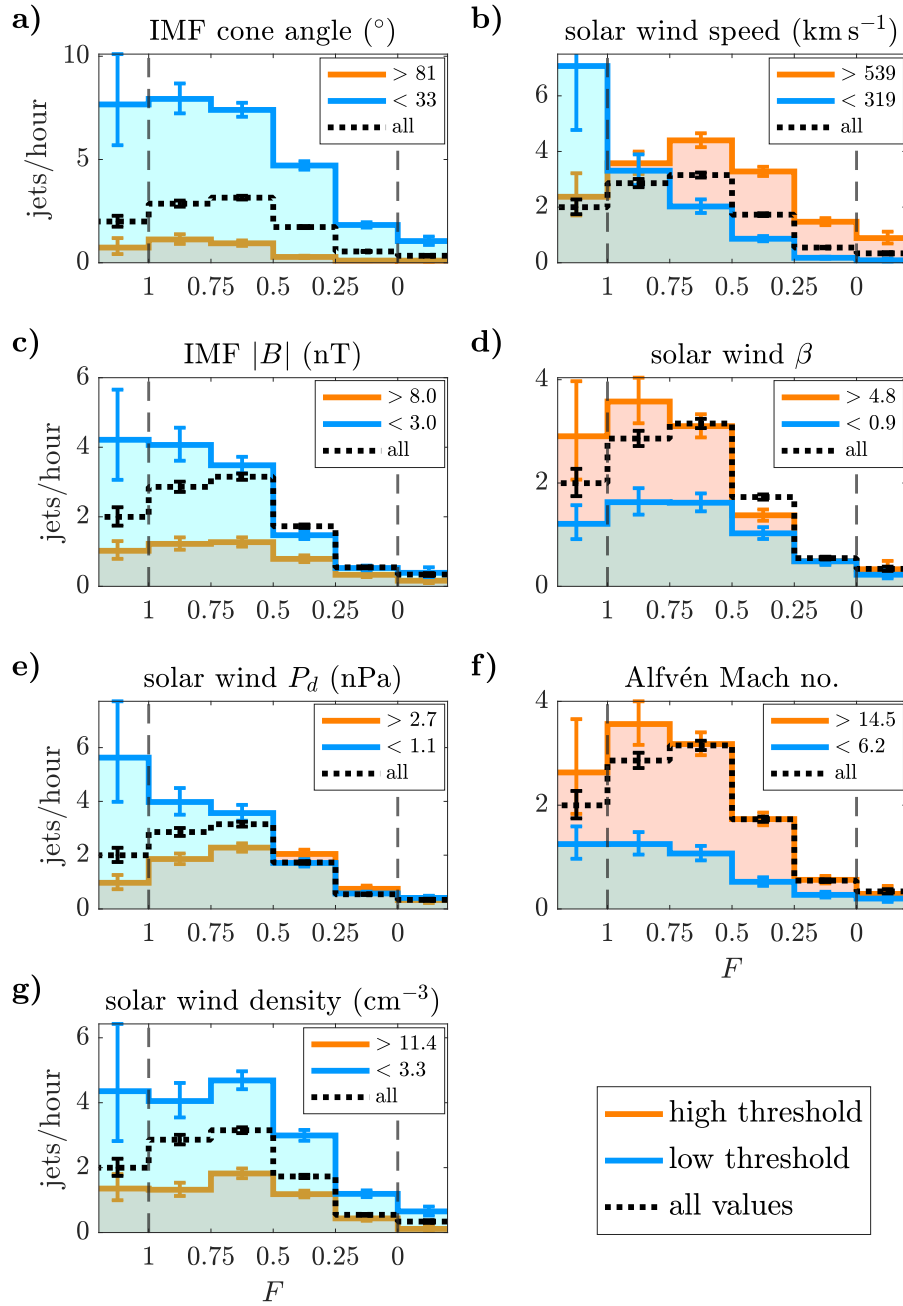


**Figure 3.7:** (Continued). e) IMF  $|B|$ ; f) plasma  $\beta$ ; g) density.

(though with different binwidth). This allows us to see how each jet subset observed under constrained solar wind conditions compares to the general population, and the factors that most strongly contribute to the shape of the curve. Note also that by comparing the left side of each plot (in particular for  $0.75 < F < 1$ ) we can clearly see the factors influencing jet formation rates at the bow shock (as explored in Figure 3.3).

The cyan histogram in Figure 3.8a, representing low cone angles, dwarfs its high cone angle counterpart throughout all regions of the magnetosheath showing that, as expected from the preceding results, jets are far more likely to reach the magnetopause under low cone angle solar wind than high cone angle solar wind. A similar, but not as strong, combined effect is seen for solar wind speed in Figure 3.8b. Quantities that display oppositely directed formation and propagation effects are particularly interesting. In Figure 3.8c we can see that for low IMF magnitude solar wind there are significantly more jets formed at the bow shock. However, due to the propagation effects described in Section 3.2.3, the observation rate falls far faster than the high IMF magnitude solar wind such that near the magnetopause the occurrence rate of jets formed from low IMF magnitude solar wind is only marginally higher than for high IMF magnitudes. This cancellation effect is even clearer in solar wind plasma  $\beta$  (Figure 3.8d) and dynamic pressure (Figure 3.8g), such that both can be said to have no overall effect on the rate of jets reaching the magnetopause.

In Table 3.1 we quantify these effects and give numerical comparisons of jet observation rates at the magnetopause for high and low values of each solar wind parameter. The multiplier in the final column is drawn from the ratio of heights of the  $0 < F < 0.25$  bars in each panel of Figure 3.8, i.e., how many more jets are expected to reach the magnetopause under one condition compared to the other. This ratio is defined to be greater than 1, with the dominant regime ('high' or 'low') shown alongside. The rates of jets per hour contributing to the calculation of the multiplier are also shown in Table 3.1, along with the actual number of jets in the data set that fall into each of the parameter constraints. Note that we do not place much emphasis on the absolute



**Figure 3.8:** Same format as Figure 3.6 except that distributions are expressed in units of jets per hour per bin spent in the magnetosheath for each restricted distribution, thus combining formation and propagation effects. The net effect on the number of jets reaching the magnetopause is calculated from the  $0 < F < 0.25$  bin. a) IMF cone angle; b) solar wind speed; c) IMF magnitude; d) solar wind plasma  $\beta$ ; e) solar wind dynamic pressure; f) solar wind Alfvén Mach number; g) solar wind density. Figure as presented in LaMoury et al. (2021).

values in jets per hour, as our selection criteria are such that smaller jets are more likely to be missed (Plaschke et al., 2020c), and our observation window is confined to the subsolar region. However, the relative observation rates under different solar wind conditions give clear indicators as to what factors are most relevant for magnetopause impacts. We therefore obtain quantitative estimates for how the changing solar wind conditions affect the likelihood of jets reaching the magnetopause.

IMF cone angle is the strongest controlling factor overall, with  $17.28^{+10.13}_{-4.59}$  times as many jets expected to reach the magnetopause under low ( $< 33^\circ$ ) angles than under high ( $> 81^\circ$ ) angles. This factor is more extreme than the factor of 9 disparity in jet occurrence rate observed by Vuorinen et al. (2019) due to the compounding of formation and propagation effects. The next largest is solar wind speed, where we see  $8.27^{+3.06}_{-1.89}$  times as many jets in front of the magnetopause when the solar wind is fast ( $> 539 \text{ km s}^{-1}$ ) compared to when it is slow ( $< 319 \text{ km s}^{-1}$ ). The final parameter to show a strong effect is solar wind density, with  $2.73^{+0.93}_{-0.60}$  times as many jets during low ( $< 3.3 \text{ cm}^{-3}$ ) density compared to high ( $> 11.4 \text{ cm}^{-3}$ ) density. The influences of low IMF magnitude and high Alfvén Mach number are more minor in comparison but still notable, each making jet impacts approximately twice as likely as their opposite conditions. This analysis is somewhat sensitive to the exact values chosen to define ‘high’ and ‘low’ thresholds. A variety of percentile thresholds were considered and tested, which produced minor changes in the multipliers calculated, meaning that the values shown in the last column of Table 3.1 should be taken as approximate indicators of the scale of each effect. The general conclusions, however, remain intact regardless of the choice of threshold values, with IMF cone angle always being the strongest controlling factor, followed by solar wind speed, then density. The only parameters examined in this study that show no clear net effect on the expected rate of jets reaching the magnetopause are the solar wind dynamic pressure and plasma  $\beta$ , both of which have error ranges that span both sides of unity, due to the oppositely directed formation and propagation effects.

**Table 3.1:** Summary of effects of solar wind conditions on the numbers of jets expected to reach the magnetopause.

| Parameter                              | High     | Low     | # (high) | # (low) | Jets/h (high)          | Jets/h (low)           | Multiplier                     |
|----------------------------------------|----------|---------|----------|---------|------------------------|------------------------|--------------------------------|
| cone angle ( $^{\circ}$ )              | $> 81$   | $< 33$  | 48       | 778     | $0.11^{+0.03}_{-0.03}$ | $1.83^{+0.13}_{-0.13}$ | $17.28^{+10.13}_{-4.59}$ (low) |
| $V_{\text{SW}}$ ( $\text{km s}^{-1}$ ) | $> 539$  | $< 319$ | 533      | 106     | $1.47^{+0.12}_{-0.13}$ | $0.18^{+0.03}_{-0.04}$ | $8.27^{+3.06}_{-1.89}$ (high)  |
| $ B $ (nT)                             | $> 8.0$  | $< 3.0$ | 90       | 250     | $0.33^{+0.07}_{-0.08}$ | $0.53^{+0.06}_{-0.07}$ | $1.59^{+0.72}_{-0.43}$ (low)   |
| $\beta$                                | $> 4.8$  | $< 0.9$ | 224      | 174     | $0.49^{+0.06}_{-0.07}$ | $0.48^{+0.07}_{-0.08}$ | $1.00^{+0.34}_{-0.25}$ (high)  |
| $P_d$ (nPa)                            | $> 2.7$  | $< 1.1$ | 176      | 326     | $0.75^{+0.11}_{-0.12}$ | $0.58^{+0.06}_{-0.07}$ | $1.30^{+0.38}_{-0.31}$ (high)  |
| $M_A$                                  | $> 14.5$ | $< 6.2$ | 241      | 98      | $0.56^{+0.07}_{-0.08}$ | $0.27^{+0.05}_{-0.06}$ | $2.06^{+0.90}_{-0.56}$ (high)  |
| $n$ ( $\text{cm}^{-3}$ )               | $> 11.4$ | $< 3.3$ | 126      | 520     | $0.44^{+0.07}_{-0.08}$ | $1.19^{+0.10}_{-0.11}$ | $2.73^{+0.93}_{-0.60}$ (low)   |

*Note.* All statistics derived from jet observations with  $0 < F < 0.25$ , i.e., immediately in front of the magnetopause. Threshold values given in columns 2 and 3 are those used to define ‘high’ and ‘low’ populations in Figures 3.6 and 3.8, i.e., 85<sup>th</sup> and 15<sup>th</sup> percentiles of each solar wind parameter in the full magnetosheath data set. Columns 4 and 5 give the number of jets in the data set that meet the criteria of  $0 < F < 0.25$  (in front of the magnetopause) under each constrained solar wind condition. Columns 6 and 7 give the expected number of jets per hour at the magnetopause under high and low solar wind parameters (i.e., the heights of the  $0 < F < 0.25$  columns in Figure 3.8, including error bars). The multiplier in column 8 is calculated as the ratio columns 6 and 7 (defined to be greater than 1). ‘High’ and ‘low’ indicate which regime is dominant in each case.

### 3.4 Discussion

Our analysis is subject to some limitations and caveats. If jets are braked during propagation, they may be slowed to the point that they are no longer detectable via our jet selection criteria (that their earthward dynamic pressure exceeds half that of the pristine solar wind). This, in part, may explain the drop-off that is seen in the black curve of Figure 3.1, potentially exaggerating the gradient if a number of weakened jets continue to propagate undetected. Similarly, Plaschke et al. (2020c) suggested that jets can fragment into several smaller jets (or merge into larger ones) as they travel, changing their cross-sectional areas, and thus the likelihood of being observed by a single spacecraft. This raises questions about where is an appropriate level to set the detection threshold, i.e., how small or slow does a jet have to become before it is no longer considered a jet? While an interesting problem, we do not consider it an issue as the focus of this investigation is understanding the conditions most relevant for magnetopause impacts. We are, therefore, most interested in larger and faster jets observed near the magnetopause, i.e., those with a greater chance of being geoeffective, which our selection criteria are most likely to capture. Note also that, in this portion of our study, we do not observe jets actually impacting the magnetopause. This is a topic of investigation in Chapter 5. However, we find it reasonable to assume that a jet observed immediately in front of the magnetopause will later go on to strike or disturb it.

A potential explanation for higher solar wind dynamic pressures increasing the likelihood of jets propagating far into the magnetosheath can be reached by considering jet travel times. Under high-dynamic pressure conditions, the magnetosheath layer is compressed and thinned, decreasing the time taken for a jet to reach the magnetopause. Similarly, we see that higher solar wind speed creates faster jets (though this is, to an extent, necessitated by our selection criteria), which are then able to reach the magnetopause in less time. This could lower the chance of a jet being broken up, though it is unlikely to be the only factor affecting the dissipation rate. Further study



should, therefore, be conducted into how jets interact with instabilities and dissipation mechanisms. Analytical modelling by Hietala and Plaschke (2013) found that low  $\beta$  solar wind produces jets with higher dynamic pressure relative to the upstream solar wind. This would likely increase their ability to propagate far into the magnetosheath, which is in line with our observations (Figure 3.6d). They also saw stronger jets during high Alfvén Mach solar wind, however we see only modest evidence for high Alfvén Mach solar wind increasing jet propagation (Figure 3.7d). This may be explained by the simulation study by Omid et al. (2016), where in high Alfvén Mach solar wind regimes, increased turbulence within the magnetosheath inhibited the propagation of jets and decreased their size.

Analysis by Turc et al. (2018) and Turc et al. (2019) of global simulations and Cluster observations showed that a higher IMF  $|B|$  causes foreshock waves to move to smaller spatial scales, which in turn creates smaller ripples on the quasi-parallel bow shock, increasing the number of potential sites for jet formation. Our results appear in contradiction to this, where we see that higher magnetic field magnitudes actually decrease the likelihood of jet formation (Figure 3.3c). However it may be the case that smaller ripples create more, but smaller, jets that are less likely to be detected by a single spacecraft.

Many of the solar wind properties studied are related. Fast solar wind is generally expected to have a lower density and a more radial magnetic field (i.e., lower cone angle), though it is generally seen to have a lower Alfvén Mach number than slow solar wind (see, e.g., Ebert et al., 2009). As fast solar wind is seen at the equator more often in times near solar maximum (e.g., McComas et al., 2003) there may therefore be a solar cycle dependence for jets impacting the magnetopause. This may explain some of the differences between the study of Plaschke et al. (2013) and our own in terms of jet occurrence rates and distributions in  $F$  (i.e., between Figure 2.5a and 2.5b in the previous chapter). The former was compiled around a deep solar minimum (2008–2011), while the latter included solar maximum (2012–2018).

Our results also suggest potential interesting links between magnetosheath jets and extreme solar wind transients, due to the way in which they modulate the conditions arriving at the bow shock. Coronal mass ejections (CMEs) are typically observed with higher speeds, densities, and magnetic field magnitudes than the ambient solar wind at 1 AU (e.g., Kilpua et al., 2017). Based on our findings, CMEs may enhance the rates of jets reaching the magnetopause by virtue of their speed, though increased density may work to counteract this. Increased magnetic field strength may reduce the absolute numbers of jets formed at the bow shock, but the likelihood of their survival to the magnetopause will be increased such that the rates of jets reaching the magnetopause are largely unaffected by the magnetic field magnitude itself. It is not clear how this conflict of parameter influences would affect the overall rate of jet formation and propagation. The potential effects may even extend beyond those arising directly from the magnetic cloud itself. Neugebauer et al. (1997) observed that extended periods of radial IMF often follow in the wake of a CME, which could enhance the numbers of jets reaching the magnetopause in the hours following a CME impact.

Following the publication of LaMoury et al. (2021), an in-depth statistical study (to which this author contributed) was conducted by Koller et al. (2022) in an attempt to resolve the conflict of parameter influence in solar wind transients. Using a database spanning 2008–2021, they studied the effect of CMEs and stream interaction regions (SIRs) on jet formation. The study built on the work presented here and studied the variation of jet observations as upstream solar wind parameters varied during the passage of these transients. Their findings are in good agreement with the results presented here, though note that they did not study the effect of these transients on jet propagation to the magnetopause.

Using superposed epoch analysis, they studied the variation of jet occurrence rates throughout CME passage, delineating different parts of the CME structures. As extremely large eruptions of plasma from the Sun, the main body of a CME is known as the magnetic ejecta, and often takes the form of a flux rope with smoothly varying

magnetic field components and high magnitude (see, e.g., Good et al., 2019). They are often seen to travel at higher speeds than the ambient solar wind leading to a pile up of material, or even a shock, at the leading edge. If a shock is present, then a region of shocked plasma exists behind it in a sheath region where plasma is compressed and turbulent, much like the magnetosheath (see, e.g., Lugaz et al., 2016).

At the leading edge of CMEs, Koller et al. (2022) saw a jump in each of their studied parameters of density, IMF magnitude, and solar wind speed, as would be expected from a shock driven by a fast-moving structure in the solar wind. This is followed by a significant drop in jet observation rates. In their superposed epoch analysis of CME observations they see that the solar wind speed stays high (at or slightly below  $500 \text{ km s}^{-1}$ ) throughout the passage, while the other two quantities gradually return to their pre-CME values, at which point the jet observation rate recovers. They conclude that CMEs have an overall effect of decreasing jet production due to the variation of the aforementioned parameters, and due to the sheath regions significantly changing the local cone angle, meaning that a stable foreshock is unable to form. This is entirely consistent with our jet formation relations (Figure 3.3), as high IMF magnitudes and densities appear to suppress jet formation, as do solar wind speeds of around  $350\text{--}500 \text{ km s}^{-1}$ .

SIRs are transient structures resulting from the interaction of portions of fast and slow solar wind streams. To form them, the high speed stream (HSS) (originating from coronal holes) catches up with a slow speed stream, causing a pile-up layer with high density, field strength, and pressure, which precedes the velocity enhancement.

During SIRs, Koller et al. (2022) see an initial drop in solar wind speed, and an enhancement in IMF magnitude and density. This is accompanied by a modest drop in jet observation rates. The magnetic field magnitude and density measurements quickly drop below their quiet time values, however, while the solar wind speed rises, leading jet observation rates to increase to a peak at the trailing edge of the SIR. They conclude that SIRs and high speed streams have the overall effect of increasing jet formation.

This reinforces our observations of high IMF magnitude and density acting to suppress jet formation, and high solar wind speeds encouraging it.

This work was recently refined by Koller et al. (2023) who further explored how the varying solar wind conditions in these transients affects jet occurrence. They concluded that in CME magnetic ejecta, a combination of high IMF cone angles and low Alfvén Mach numbers inhibit jet production, while in HSSs, associated low cone angles, low densities, and low magnetic field strengths enhance jet occurrence. This serves as further validation of the work presented here.

### 3.5 Summary and Conclusion

Using our database of 13,096 jets seen by the THEMIS spacecraft from 2008 to 2018 we have performed statistical analysis to determine how upstream solar wind conditions (obtained from OMNI) affect the likelihood of jets forming at the bow shock and then propagating to the magnetopause without dissipating. We find that a number of parameters increase the likelihood of jets forming at the bow shock, the most favourable conditions being: low IMF cone angle, solar wind speeds of  $\sim 300 \text{ km s}^{-1}$  or  $\sim 600 \text{ km s}^{-1}$ , low IMF magnitude, high  $\beta$ , low dynamic pressure, high Alfvén Mach number, and low density. We find that once jets are formed at the bow shock, their likelihood of surviving throughout propagation to the magnetopause is also controlled by the upstream solar wind conditions. The conditions most favourable for this are: low IMF cone angle, high solar wind speed, high IMF magnitude, low  $\beta$ , and high dynamic pressure. Combining these two effects, we find that higher numbers of jets reach, and therefore likely impact, the magnetopause when the solar wind exhibits a low IMF cone angle, high wind speed, high Alfvén Mach number, and low density. Solar wind  $\beta$  and dynamic pressure display no net effect on the rates of jets reaching the magnetopause.

It is notable that several of these properties are associated with fast solar wind and

extreme solar wind transient events, and therefore may be modulated by the solar cycle. Under fast solar wind conditions the highest impact rates of jets on the magnetopause are expected, increasing the likelihood of them affecting magnetospheric dynamics and potentially inducing space weather effects. Follow-up studies have now verified our observed jet formation relationships in the context of solar wind transient structures, finding that CME impacts decrease the likelihood of jet formation, while SIRs increase it. Our findings provide a useful step towards eventual space weather forecasting regimes whereby we will be able to predict the inner-magnetosphere effects of magnetosheath jets purely from measurements of the solar wind upstream of the bow shock. In the next chapter we make another step towards this by investigating the properties of jets reaching the magnetopause and making predictions for their likely influence on magnetic reconnection.

# Chapter 4

## Jet Properties and $\beta$ -Shear Relation for Reconnection

### 4.1 Introduction

In the previous Chapter we determined the solar wind conditions most favourable for jets to reach and impact the magnetopause. We now turn our attention to the properties of jets within the magnetosheath. In particular, we are interested in the properties of jets observed near magnetosheath boundaries to help understand how they evolve and how the magnetosheath filters the propagation of certain jets. At the magnetopause, we study jet properties relevant for reconnection and make predictions for how they may modify localised reconnection at the magnetopause.

In their statistical study of jet  $B_Z$  at the magnetopause, Vuorinen et al. (2021) studied the proportion of jet plasma carrying  $B_Z$  oppositely directed to the upstream IMF orientation. When considering all plasma contained within jet intervals, they found that, in their data set of 2,859 jets,  $25^{+4}_{-4}$  % of jet plasma during periods of southward IMF had a GSM  $B_Z$  pointed northward, while  $37^{+6}_{-5}$  % of jet plasma during times of northward IMF contained southward  $B_Z$ .

They also sought to determine the fraction of jets that contained any pulse of  $B_Z$  oppositely directed to the IMF at the time, finding that  $62^{+6}_{-5}$  % of jets observed during southward IMF contained some amount of northward IMF, while  $72^{+5}_{-6}$  % of jets observed during northward IMF contained some amount of southward-pointing  $B_Z$ . This means that the majority of jets contain some amount of magnetic field which could potentially alter reconnection at the magnetopause from what would typically be expected based on the IMF orientation. Crucially, they found these fractions to be significantly higher than those of non-jet magnetosheath plasma sampled during similar conditions, meaning jets are a strong source of oppositely directed  $B_Z$  arriving at the magnetopause.

With our larger jet data set we are able to test and verify these statistics using the same process and criteria as Vuorinen et al. (2021). Specifically, using jets observed between  $F$  values of -0.1 and 0.3 (i.e., near the magnetopause) we find that jet plasma during southward IMF exhibits northward  $B_Z$  27 % of the time, while 37 % of jet plasma during northward IMF is pointed southward. When examining the fraction of jets that contain any pulse of oppositely directed  $B_Z$ , we find that 57 % of jets during southward IMF contain a northward pulse, while 72 % of jets during northward IMF contain a southward pulse.

These numbers are in very good agreement with Vuorinen et al. (2021), with each of our values lying within their given uncertainty ranges. This suggests that, on the basis of their magnetic field orientations, the majority of jets in our data set would potentially be able to modify reconnection at the magnetopause from what would be expected from the IMF orientation, triggering it during times of northward IMF, or suppressing it during southward IMF. In this chapter, we perform statistical studies on the properties of jets in the magnetosheath, and in particular those relevant for reconnection. We compare jets observed near the bow shock and near the magnetopause to understand how their properties may evolve or be filtered through propagation. We then combine properties to make statistical predictions for how jets might affect reconnection at the

magnetopause according to the  $\beta$ -shear relation (Swisdak et al., 2010; Phan et al., 2013; see Section 1.1.3 for further information).

## 4.2 Data and Methods

In this study we make use of the same THEMIS jet list described previously. We focus on those observed near the magnetosheath boundaries, that is the 1,924 jets observed near the magnetopause ( $F < 0.25$ ) and 1,739 near the bow shock ( $F > 0.75$ ). Where in the previous chapter we typically characterised each jet by the associated measurements at time  $t_0$  (the point of maximum magnetosheath to solar wind dynamic pressure ratio), here we make use of all the plasma contained within jet intervals (defined as all points around  $t_0$  where the dynamic pressure ratio exceeds 0.25) in order to study jets as complete and variable entities. We study quantities most relevant for reconnection and the geoeffectiveness of jets (see Section 1.4.4). This includes magnetic field orientation (specifically the GSM-Z component), temperature, pressure components (thermal, magnetic, and dynamic), and plasma  $\beta$ . We compare distributions of these quantities for jets and the non-jet magnetosheath, in different magnetosheath regions, and during different IMF orientations (from the OMNI database).

### 4.2.1 Calculation of $\Delta\beta$ -shear relation parameters

To make predictions for how jets may affect reconnection in a statistical sense, we build on the study of Vuorinen et al. (2021) to consider not just the Z component of the magnetic field, but the whole of the  $\beta$ -shear condition for reconnection (Equation 1.9). This requires estimating the shear angle each plasma parcel makes with the magnetospheric field at the magnetopause, and the  $\Delta\beta$  across the magnetopause layer. As each in situ magnetosheath measurement is not necessarily associated with a magnetopause crossing, these parameters cannot be directly calculated. Instead, we make some assumptions in order to predict whether a plasma parcel near the magnetopause would be likely to reconnect (or not) when it reaches the boundary.



In order to estimate the magnetic shear angle between plasma in the magnetosheath and magnetosphere, the process is as follows. The magnetic field of the magnetosphere is assumed to be exactly northward, that is, directed purely in the positive GSM-Z direction. The magnetic shear angle is then calculated as the angle between the projection of the magnetosheath field vector on the GSM Y-Z plane, and the Z axis, such that a  $0^\circ$  shear represents parallel vectors (where reconnection would not be expected), while a shear of  $180^\circ$  is antiparallel, and in the idealised picture of reconnection.

To estimate the  $\beta$  asymmetry, it is assumed that  $\beta$  within the magnetosphere is negligibly small compared to  $\beta$  in the magnetosheath, making magnetosheath  $\beta$  a proxy for  $\Delta\beta$ .

The current sheet width,  $L$ , is assumed to be on the order of the ion inertial length, i.e.,  $L = 1 d_i$ . This is consistent with assumptions made by Phan et al. (2013) in their study of magnetopause current sheets crossings. These assumptions made, we can reformulate the relation for reconnection suppression as

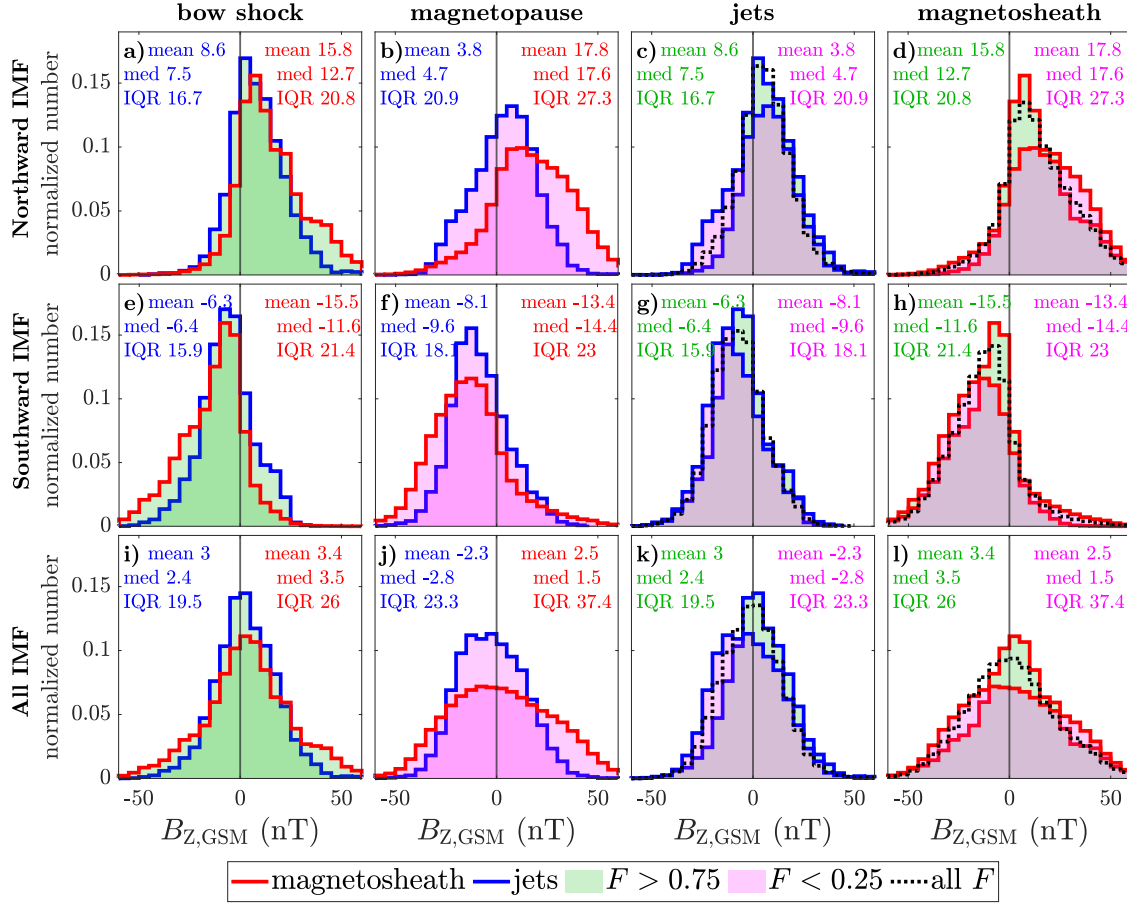
$$\beta_{\text{msh}} > 2 \tan(\theta/2). \quad (4.1)$$

We calculate the percentage of plasma that satisfies this condition to predict what proportion is likely to suppress reconnection. Current sheet widths of  $L = 2 d_i$  and  $L = 0.5 d_i$  are used to give an uncertainty range on the calculated values. This is consistent with the methods used by Phan et al. (2013).

## 4.3 Results

### 4.3.1 In situ properties of jets near the bow shock and magnetopause

Figure 4.1 shows distributions of  $B_{Z,\text{GSM}}$  measured in the magnetosheath, for both jets and magnetosheath data, separated by IMF orientation and observation location. In this figure (and subsequent figures in this section), blue lines represent jet observations,



**Figure 4.1:** Histograms of  $B_{Z,GSM}$  measured in the magnetosheath. Panels a)–d) during northward IMF; e)–f) southward IMF; i)–l) all IMF. First column: jets vs magnetosheath measured near the bow shock; second column: jets vs magnetosheath measured near the magnetopause; third column: jets near the bow shock vs jets near the magnetopause; fourth column: magnetosheath near the bow shock vs magnetosheath near the magnetopause. Each panel shows the mean, median, and inter-quartile range of the distributions, colour coded accordingly.

while red represents magnetosheath. Green shaded regions denote observations made near the bow shock ( $F > 0.75$ ), while magenta shading denotes observations near the magnetopause ( $F < 0.25$ ). Black dashed lines show the corresponding distributions for all  $F$  values. In each panel, the mean, median, and inter-quartile range (IQR) of each distribution is shown, colour coded according to the data to which they refer. This allows us to make quantitative comparisons on their locality and spread.

Comparing jets and magnetosheath near the bow shock (Figures 4.1a, 4.1e, and 4.1i), we see that the distributions for jets are typically narrower on average than the mag-

netosheath in general, displaying a smaller inter-quartile ranges. Jet distributions tend to be more centred on zero, with a lower median during northward IMF and larger during southward IMF, therefore displaying a greater proportion of magnetic field oppositely directed to the IMF than the magnetosheath plasma. Plaschke et al. (2020d), following the simulations of Karimabadi et al. (2014), studied how jets modify the magnetic field orientation in the magnetosheath during their passage. They found that jets generally align the magnetosheath magnetic field with the jet velocity vector and that this effect is particularly strong near the bow shock. Our results are consistent with this idea. For predominantly X-directed jets, a field rotation to align with the velocity vector would have the effect of decreasing the Z-component compared to the standard magnetosheath flow, which can be seen here.

This difference is also pronounced for observations made close to the magnetopause (Figures 4.1b, 4.1f, and 4.1j), particularly during northward IMF where the  $B_Z$  distribution for jets is centred slightly above zero (median 4.7 nT), compared to the magnetosheath distribution which is majority northward (median 17.6 nT). Though we do not filter by other solar wind parameters as was done by Vuorinen et al. (2021), our results appear to broadly support the findings of their study and imply that during northward IMF, when magnetopause reconnection is not typically favourable, jets may be able to produce the magnetic shear required to stimulate local reconnection. Similarly, we would expect jets to suppress reconnection during southward IMF more often than the regular magnetosheath plasma. It should be noted, however, that the  $B_{Z,GSM}$  distributions show greater difference between jets and magnetosheath for northward IMF than southward IMF.

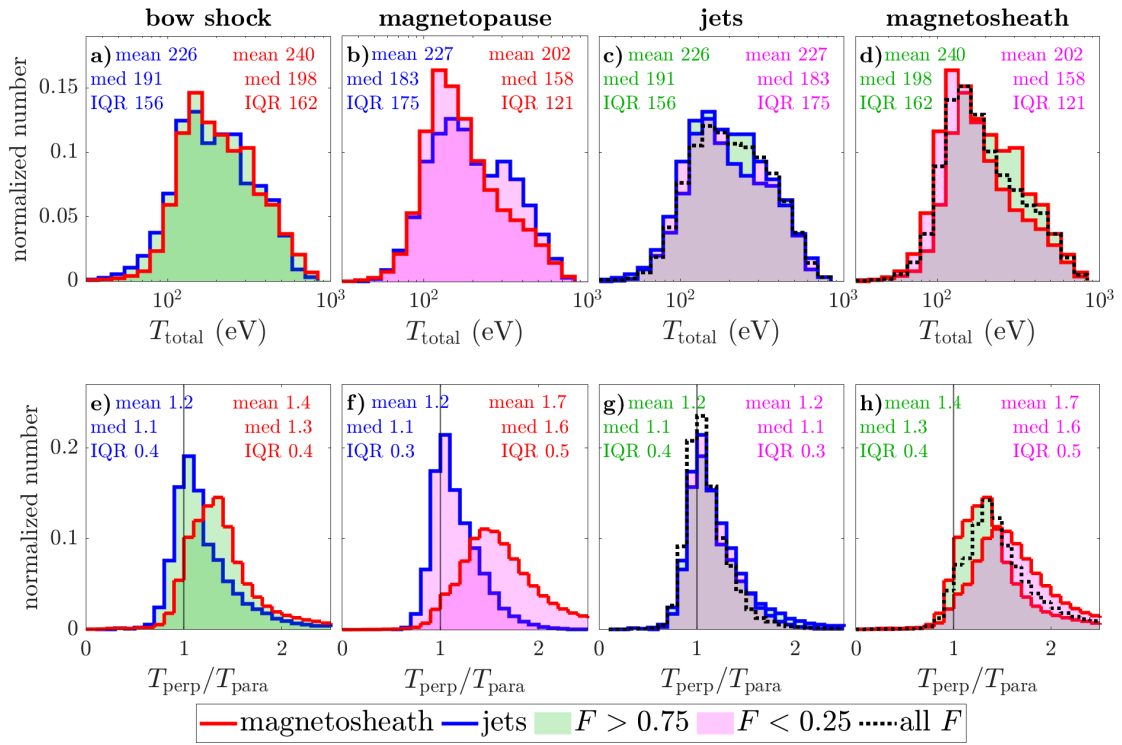
We see that the  $B_Z$  distributions within jets do not appear to be drastically different at the bow shock compared to the magnetopause, with medians and inter-quartile ranges differing by only a few nT. There is, however, some evidence to suggest that  $B_Z$  distributions in jets near the magnetopause are more typically slightly more southward (Figures 4.1c, 4.1g, and 4.1k). This appears to be the case for both northward and south-

ward IMF. There is no reason to suggest that jet magnetic fields would preferentially turn southward during propagation, so it is assumed that this is a sampling effect.

The general magnetosheath distributions (Figures 4.1d, 4.1h, and 4.1l) are similar at the bow shock and the magnetopause, though the magnetopause distributions display a greater inter-quartile range in each case, while the distribution medians tend to slightly higher  $B_{Z,GSM}$  magnitudes than at the bow shock. This can be interpreted as a pile up of flux at the magnetopause forcing the field to be more aligned with the boundary.

Figure 4.2 shows total temperature and temperature anisotropy distributions in the magnetosheath. The figure format is the same as in Figure 4.1. We see from Figure 4.2a that, at the bow shock, the total temperatures measured in jets are typically very similarly distributed to the magnetosheath at large with median values of and 191 eV and 198 eV, respectively. Near the magnetopause (Figure 4.2b), however, there is a notable difference with jets seen at somewhat higher temperatures than the surroundings. The median jet temperature in this region is 183 eV for jets, and 158 eV for the magnetosheath. It is clear then that the disparity is due to a drop in average magnetosheath temperature from bow shock to magnetopause (Figure 4.2d), while jet temperatures remain broadly unchanged from the bow shock to the magnetopause, with the median temperature dropping by just 8 eV (Figure 4.2c). This is somewhat at odds with previous studies such as those by Archer et al. (2012) and Dmitriev and Suvorova (2012) who reported an overall temperature decrease in jets compared to their surroundings. Plaschke et al. (2013) showed statistically that jets bring a cooling effect to the magnetosheath compared to the intervals immediately preceding them. In order to simulate a fairer comparison, we can restrict the magnetosheath distribution to just those during low cone angle solar wind, that being when jets are most likely to form. Taking cone angles of less than  $30^\circ$  near the magnetopause, we then find the median magnetosheath temperature to be 189 eV, which is marginally higher than that of jets under the same conditions (177 eV).

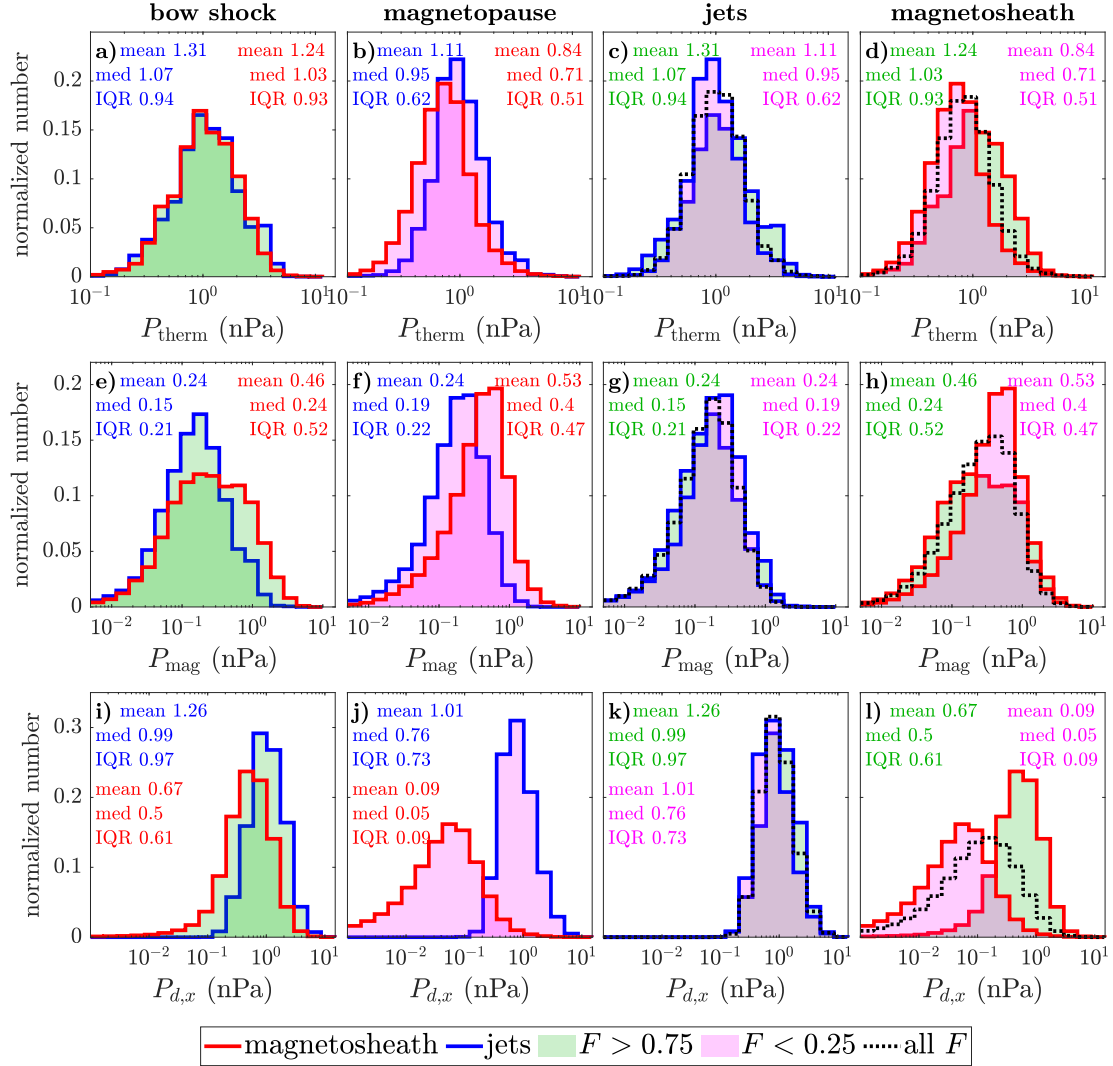
Figures 4.2e–h show temperature anisotropy, that is, the perpendicular component of



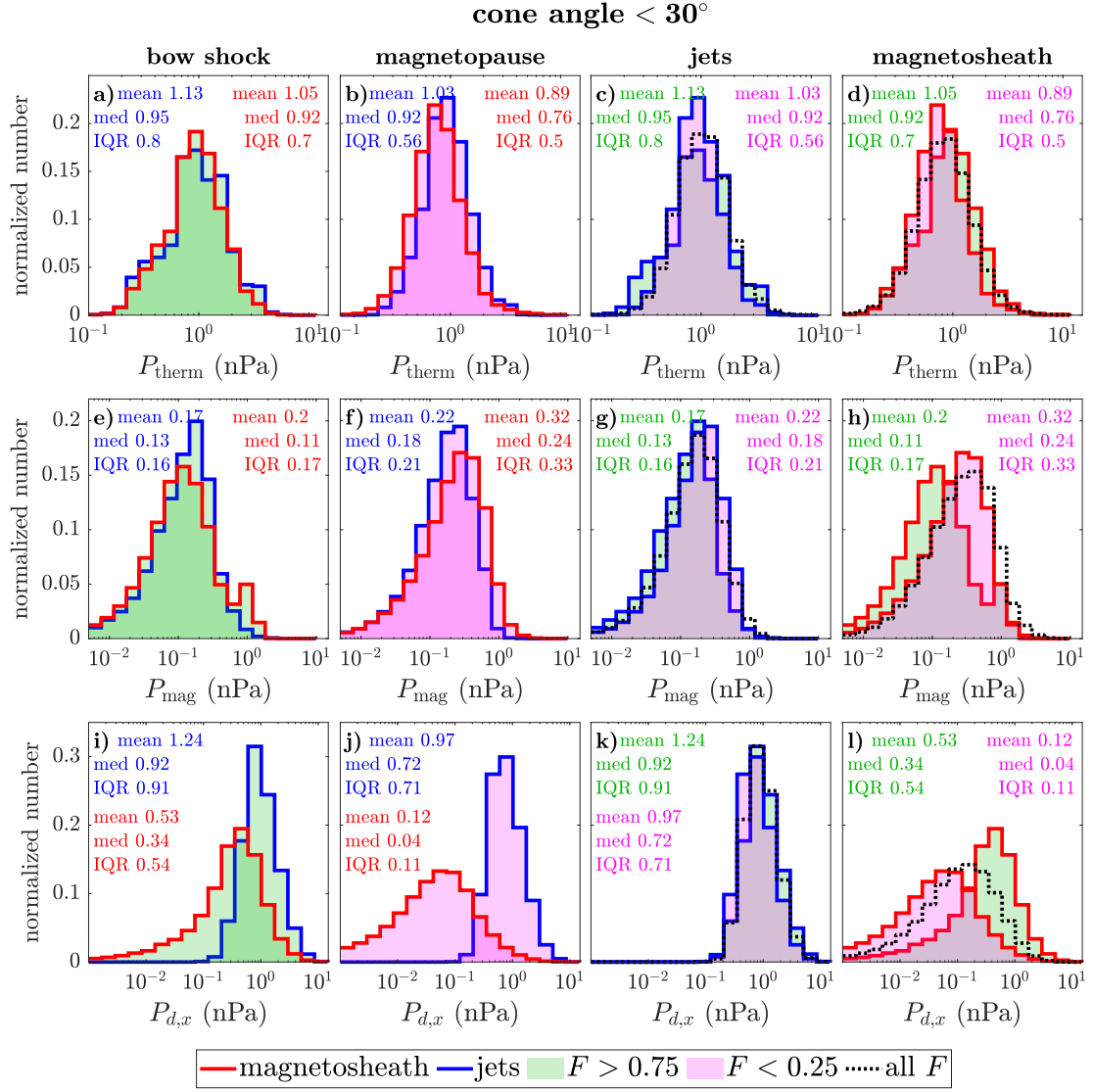
**Figure 4.2:** Temperature distributions measured in the magnetosheath. Panels a)–d) total temperature histograms in the magnetosheath; e)–h) temperature anisotropy. First column: jets vs magnetosheath measured near the bow shock; second column: jets vs magnetosheath measured near the magnetopause; third column: jets near the bow shock vs jets near the magnetopause; fourth column: magnetosheath near the bow shock vs magnetosheath near the magnetopause. Each panel shows the mean, median, and inter-quartile range of the distributions, colour coded accordingly.

temperature divided by the parallel component. We see that jet temperatures are more isotropic than the magnetosheath in general, with a median anisotropy of 1.1 at both the bow shock (Figure 4.2e) and the magnetopause (Figure 4.2f), predominantly due to the perpendicular component of the temperature being diminished in jets. The disparity is greatest at the magnetopause, where the magnetosheath has a median anisotropy of 1.6. This is in good agreement with the findings of Plaschke et al. (2013).

Figure 4.3 shows the distributions of thermal, magnetic, and dynamic pressure measured in the magnetosheath. We see that the distribution of thermal pressures measured in jets near the bow shock is almost identical to that of the magnetosheath in general, with the difference in the distribution medians much smaller than the IQRs (Figure 4.3a). At the magnetopause, however, jets typically have higher thermal pressures than



**Figure 4.3:** Pressure distributions measured in the magnetosheath. Panels a)–d) thermal pressure; e)–h) magnetic pressure; i)–l) X-directed dynamic pressure. First column: jets vs magnetosheath measured near the bow shock; second column: jets vs magnetosheath measured near the magnetopause; third column: jets near the bow shock vs jets near the magnetopause; fourth column: magnetosheath near the bow shock vs magnetosheath near the magnetopause.



**Figure 4.4:** Same as Figure 4.3, though restricted to times with IMF cone angle  $< 30^\circ$  to better mimic magnetosheath conditions during the majority of jet observations.

their surroundings, with a median of 0.95 nPa versus 0.71 nPa (Figure 4.3b). The average thermal pressure of jets near the magnetopause is very similar to those near the bow shock, with a difference in median of 0.12 nPa (Figure 4.3c), therefore the discrepancy with surroundings can be mostly attributed to a drop in thermal pressure in the regular magnetosheath flow from bow shock to magnetopause, which falls by 0.32 nPa (Figure 4.3d). This is not in agreement with the 2D simulation results of Palmroth et al. (2021), who found that jets typically thermalise with their surroundings during propagation.

The median magnetic pressure in jets is typically lower than in the surrounding magnetosheath at both the bow shock and the magnetopause (Figures 4.3e and 4.3f), with the median (and mean) magnetic pressure in jet intervals being around half that of the magnetosheath. However, magnetic pressure is typically marginally higher near the magnetopause than near the bow shock, which is seen to some extent in jets (difference in medians of 0.04 nPa, Figure 4.3g) but more so in the magnetosheath in general (difference in medians of 0.16 nPa, 4.3h). This is believed to be due to the layer of piled-up magnetic flux that accumulates at the magnetopause, particularly under northward IMF when there is less likely to be ongoing magnetic reconnection to transport the flux (in the subsolar region).

Plaschke et al. (2013) found that the magnetic pressure observed in the magnetosheath before a jet observation was typically lower than the magnetic pressure during measured jet intervals. This is in contradiction to Figures 4.3d and 4.3e, where magnetic pressure in jets is typically lower than in the magnetosheath on average. However, when restricted to low cone angle solar wind ( $< 30^\circ$ , Figure 4.4), which better mimics the pre-jet intervals used in that study by filtering for the typical magnetosheath condition when jets are most present, we find that the magnetic pressure observed in jets very similar and in fact marginally higher than the surrounding magnetosheath shortly downstream of the bow shock (medians of 0.13 nPa and 0.11 nPa, Figure 4.4e). At the magnetopause, jets exhibit a lower magnetic pressure than the magnetosheath as before, though the disparity is smaller than for all cone angle solar wind conditions,

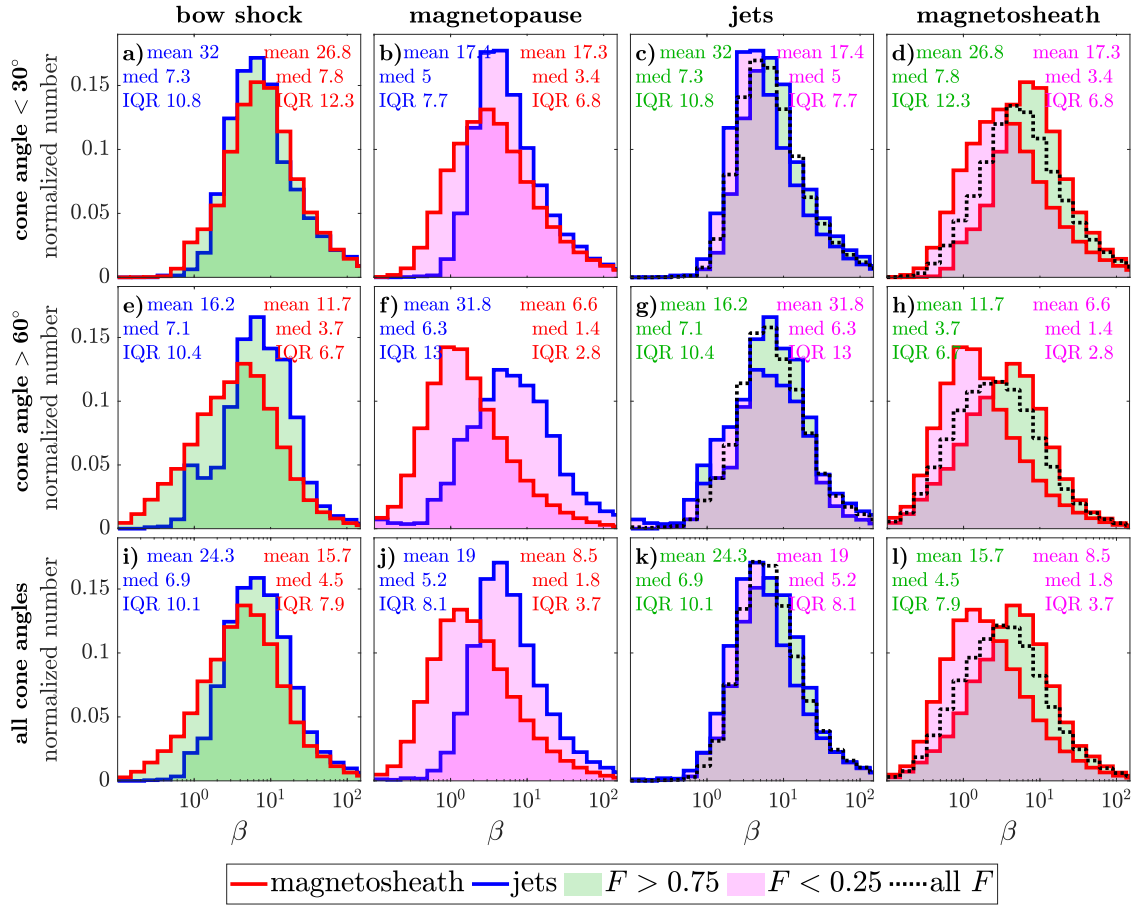


the difference narrowing from 0.21 nPa to 0.05 nPa.

Figures 4.3i-l show measurements of dynamic pressure in the magnetosheath, calculated using the X-component of velocity, i.e., flow parallel to the Sun-Earth line. As jets are selected on the basis of high dynamic pressure (relative to the upstream solar wind), it is not surprising that jets display a far higher dynamic pressure than the magnetosheath on average. Near the bow shock (Figure 4.3i), jets are seen with a median dynamic pressure of 0.99 nPa, versus 0.50 nPa for the magnetosheath in the same region. Considering the peak dynamic pressure of each jet (measured at  $t_0$ ), this rises to 1.61 nPa.

At the magnetopause (Figure 4.3j), the disparity between the two distributions is far greater, with jet and magnetosheath medians of 0.76 nPa and 0.05 nPa, respectively. It is notable that the dynamic pressure seen within jets at the magnetopause is only marginally lower than those at the bow shock (a median drop of 0.23 nPa, Figure 4.3k), while there is a much greater drop in pressure for the non-jet magnetosheath (0.45 nPa, Figure 4.3l). This would suggest that near the magnetopause, there is a greater pressure imbalance between jets and their surroundings, which would make them more prone to instabilities, diffusion, and erosion. However, it is important to be aware of the potential selection bias here. As we select jets according to their magnetosheath to solar wind dynamic pressure ratio and not relative to the local background magnetosheath (as was done by Archer and Horbury, 2013), we would most likely not detect jets whose dynamic pressures fall in accordance with the drop in background pressure. This means that the number of jets reaching the magnetopause is likely far higher than we count, though these are weaker and so by our imposed definition are no longer considered to be jets. Examining this aspect during low cone angle conditions (Figure 4.4), we see the same effects, though the pressure differences are somewhat lower, e.g., a jet to non-jet median difference of 0.68 nPa at the magnetopause during low cone angle solar wind, compared to 0.71 nPa for all cone angles.

Figure 4.5 shows distributions of  $\beta$ , the ratio of thermal and magnetic pressure, sepa-



**Figure 4.5:** Distributions of plasma  $\beta$  measured in the magnetosheath. Panels a)–d) IMF cone angle  $< 30^\circ$ ; e)–h) cone angle  $> 60^\circ$ ; i)–l) all cone angles. First column: jets vs magnetosheath measured near the bow shock; second column: jets vs magnetosheath measured near the magnetopause; third column: jets near the bow shock vs jets near the magnetopause; fourth column: magnetosheath near the bow shock vs magnetosheath near the magnetopause. Each panel shows the mean, median, and inter-quartile range of the distributions, colour coded accordingly.

rated by cone angle. We see that, on average,  $\beta$  is marginally higher for jets than non-jets at the bow shock (Figure 4.5i), with medians of 6.9 and 4.5, respectively. It appears that this difference stems primarily from high cone angle measurements (Figure 4.5e), as there is a much smaller difference (0.5) between jets and magnetosheath near the bow shock under low cone angles (Figure 4.5a). At the magnetopause, however, the difference is more pronounced, with a median magnetosheath  $\beta$  of 1.8 versus 5.2 for jets (Figure 4.5j). This too is primarily driven by measurements during higher cone angle solar wind (Figure 4.5f), with only a small difference (1.6) seen during low cone angle solar wind (Figure 4.5b).

Jets themselves are typically seen to have slightly higher  $\beta$  at the bow shock than at the magnetopause (Figure 4.5k), though the difference in medians is marginal, at 1.7 for all cone angles. This is true for both low and high cone angle solar wind (Figures 4.5c and 4.5g). As before, it is the general magnetosheath plasma that displays the greatest difference from bow shock to magnetopause, with  $\beta$  at the bow shock around twice as high on average (Figure 4.5l). This is likely due to the pile up of magnetic flux at the magnetopause. We see that the magnetosheath  $\beta$  shortly downstream of the bow shock is lower during high IMF cone angles than for low cone angles, with a median difference of 4.1. This can be understood by considering the Rankine-Hugoniot jump conditions for shocks (see Section 1.1.2). In this system, the component of the magnetic field tangential to the shock normal increases across the shock, while the normal component remains unchanged. For high cone angles, it is the tangential component that dominates, and therefore experiences a greater increase across the shock than for low cone angles. Therefore, the overall magnetic field magnitude will be higher and the  $\beta$  lower during high cone angle solar wind.

The fact that  $\beta$  at the magnetopause is typically higher for jets than the magnetosheath in general is a significant and interesting result with regard to understanding the role of jets in reconnection. Higher  $\beta$  in jets means a greater difference in  $\beta$  with the magnetosphere, lowering the likelihood of reconnection onset and making jets more

likely to suppress reconnection at the magnetopause (Swisdak et al., 2010).

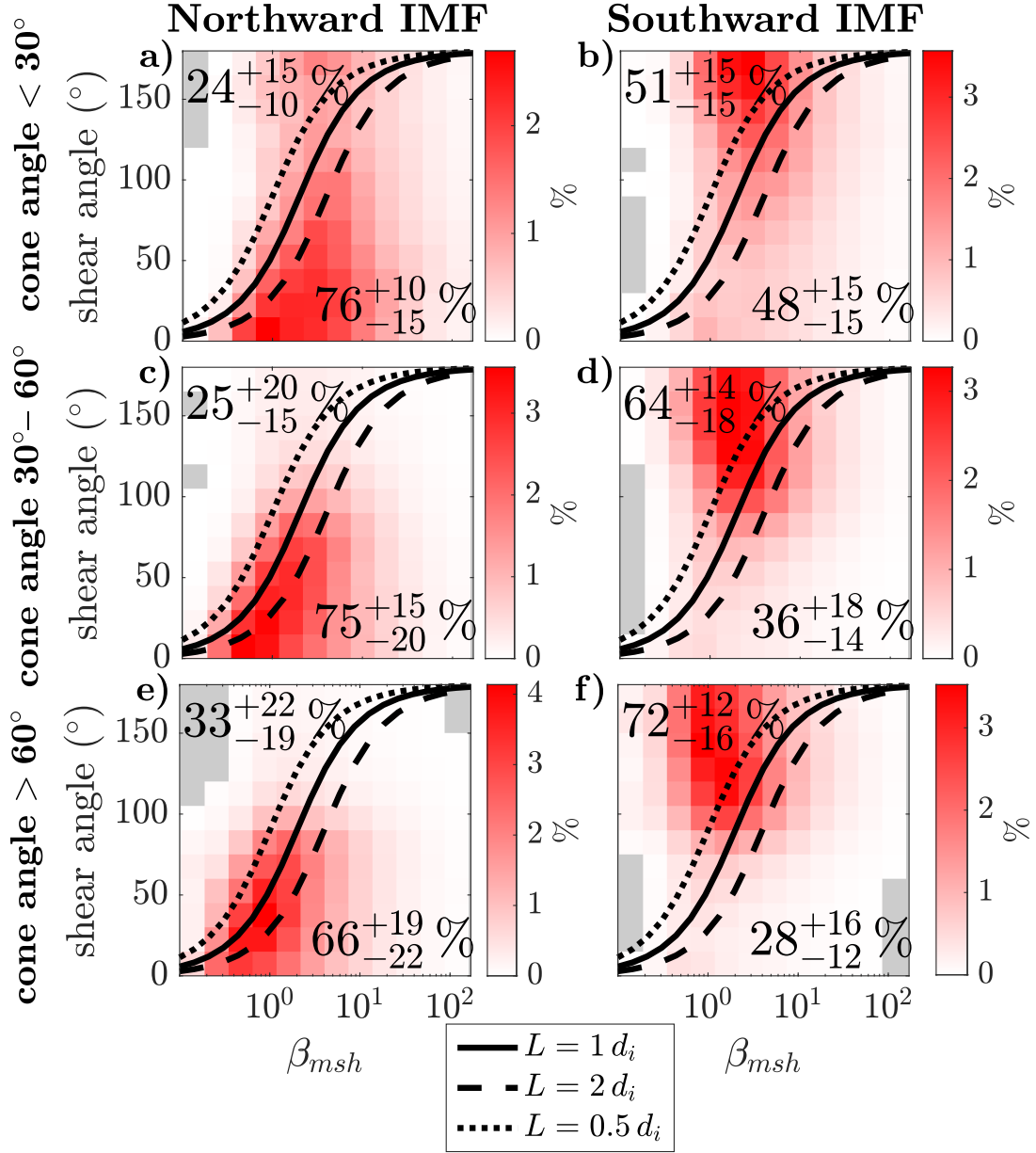
### 4.3.2 $\Delta\beta$ -shear condition for reconnection

We have seen that the magnetic field within jets is typically more variable than the magnetosheath in general, such that jets more frequently contain pulses of  $B_z$  oppositely directed to the IMF (Vuorinen et al., 2021 and Figure 4.1). This would imply that jets may be able to trigger localised reconnection at times when it wouldn't traditionally be expected, i.e., during northward IMF. This is also what was inferred by Nykyri et al. (2019). However, we have also just seen that jets generally have a higher  $\beta$  at the magnetopause than is typical for the plasma environment. This would increase the  $\Delta\beta$  term in Equation 1.9, which would then have the effect of suppressing reconnection. This presents an interesting problem, and it is not immediately clear which effect is likely to dominate, and how jets would be expected to influence reconnection in a statistical sense.

To examine this competition, we place observations in the  $\Delta\beta$ -magnetic shear parameter space, as has been done previously in reconnection studies such as that of Phan et al. (2013) (more details in Section 1.3 and Figure 1.8) and Gosling and Phan (2013). As described in Section 4.2.1, we make several assumptions in order to perform this parameterisation for plasma parcels observed shortly in front of the magnetopause without requiring simultaneous measurements inside the magnetosphere.

Using the methods and assumptions described in Section 4.2.1, we can calculate the proportion of non-jet magnetosheath plasma near the magnetopause ( $F < 0.25$ ) that fulfils the criteria for reconnection. We find that  $66^{+14}_{-16}$  % of plasma during southward IMF would be suitable to trigger reconnection, and  $29^{+21}_{-16}$  % during northward IMF.

Figure 4.6 shows 2D histograms of the  $\beta$ -shear properties of the magnetosheath near the magnetopause, separated by IMF orientation. The top-left corner of each panel shows proportion of data for which reconnection is allowed, assuming  $L = 1 d_i$ . The



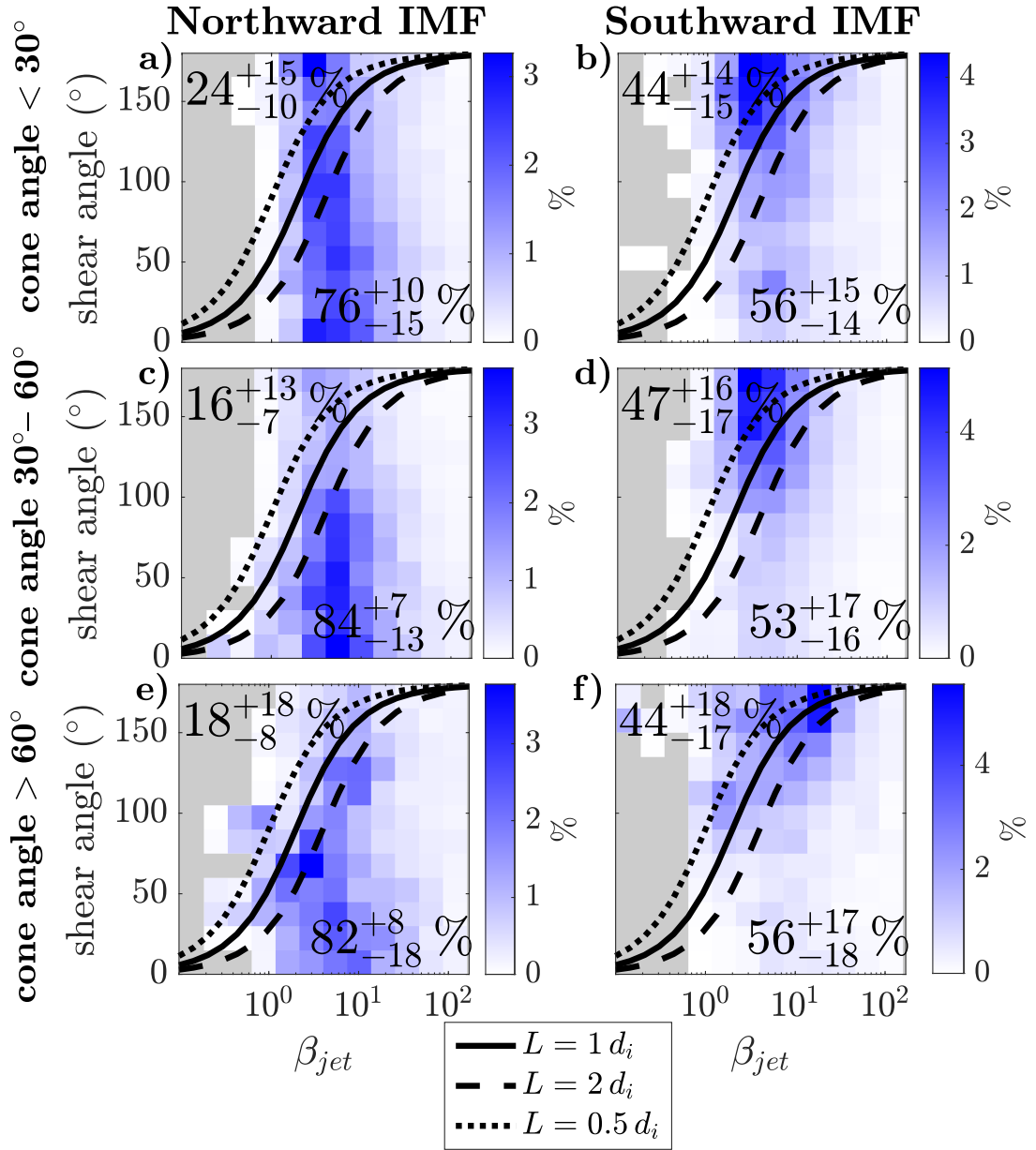
**Figure 4.6:**  $\beta$ -shear plots of near-magnetopause plasma in the non-jet magnetosheath. Colour intensity indicates the fraction of observations within a given bin, grey indicates no data. The solid line represents the limit of the inequality  $\Delta\beta > 2(L/d_i) \tan(\theta/2)$ , where  $L/d_i$  is taken to be unity. Data above the line are expected to be favourable to reconnection, while data below the line indicate plasma expected to suppress reconnection. Dashed lines indicate the position of this boundary if we instead take  $L = 2 d_i$  or  $L = 0.5 d_i$ . Labelled percentages indicate the proportion of data either side of the  $L = 1 d_i$  line, while the uncertainties indicate the change in this value produced by moving the boundary to either of the dashed lines. Left column: during times of northward IMF; right column: southward IMF; a) & b): during IMF cone angles  $< 30^\circ$ ; c) & d): cone angles  $30^\circ - 60^\circ$ ; e) & f): cone angles  $> 60^\circ$ .

uncertainty values are given by moving the dividing threshold to  $L = 2 d_i$  and  $L = 0.5 d_i$ . The bottom-right corner of each panel shows the proportion of magnetosheath plasma for which reconnection would be expected to be suppressed.

We see that during northward IMF (Figures 4.6a, 4.6c, and 4.6e) the majority of data lie beneath the  $L = 1 d_i$  line, i.e., in the zone where reconnection is expected to be suppressed. Similarly, under southward IMF (Figures 4.6b, 4.6d, and 4.6f), the majority of data is in the zone when reconnection is expected, in the top left corner. This serves as a broad validation of our methods, as the calculated distributions align with what would be expected from typical Dungey-type magnetopause reconnection, i.e., reconnection mainly occurs during southward IMF. There is, however, a large degree of variability. This is particularly clear during southward IMF at a low cone angle (Figure 4.6b), where only a very slight majority of data are in the reconnection favourable zone. It is perhaps likely therefore that quasi-radial IMF results in a more variable magnetic field draping pattern within the magnetosheath, and so there are more likely to be parcels of plasma with magnetic fields oppositely directed to the IMF arriving at the magnetopause. It is not clear, however, why we don't see a similar pattern during northward IMF in terms of the fraction of data in the reconnection-allowed zone. We note, though, that Figure 4.6a for low cone angle northward IMF shows a greater degree of spread in shear angle than the higher cone angle equivalents, which is supportive of the idea of a more variable draping pattern during radial IMF.

Having established what is typical for the non-jet magnetosheath, we can then compare the  $\beta$ -shear properties of jets. Near the magnetopause, taking all plasma contained within jet intervals, we find that during southward IMF  $45^{+15}_{-16}$  % of jet plasma is suitable for reconnection, and  $19^{+16}_{-8}$  % during northward IMF. We can immediately see that a smaller fraction of jet plasma is reconnection favourable than the non-jet magnetosheath, regardless of IMF orientation. This is likely due to the heightened  $\beta$  that is typically seen in jets at the magnetopause (Figure 4.5).

Figure 4.7 shows the  $\beta$ -shear distribution for jets, split by IMF orientation and cone



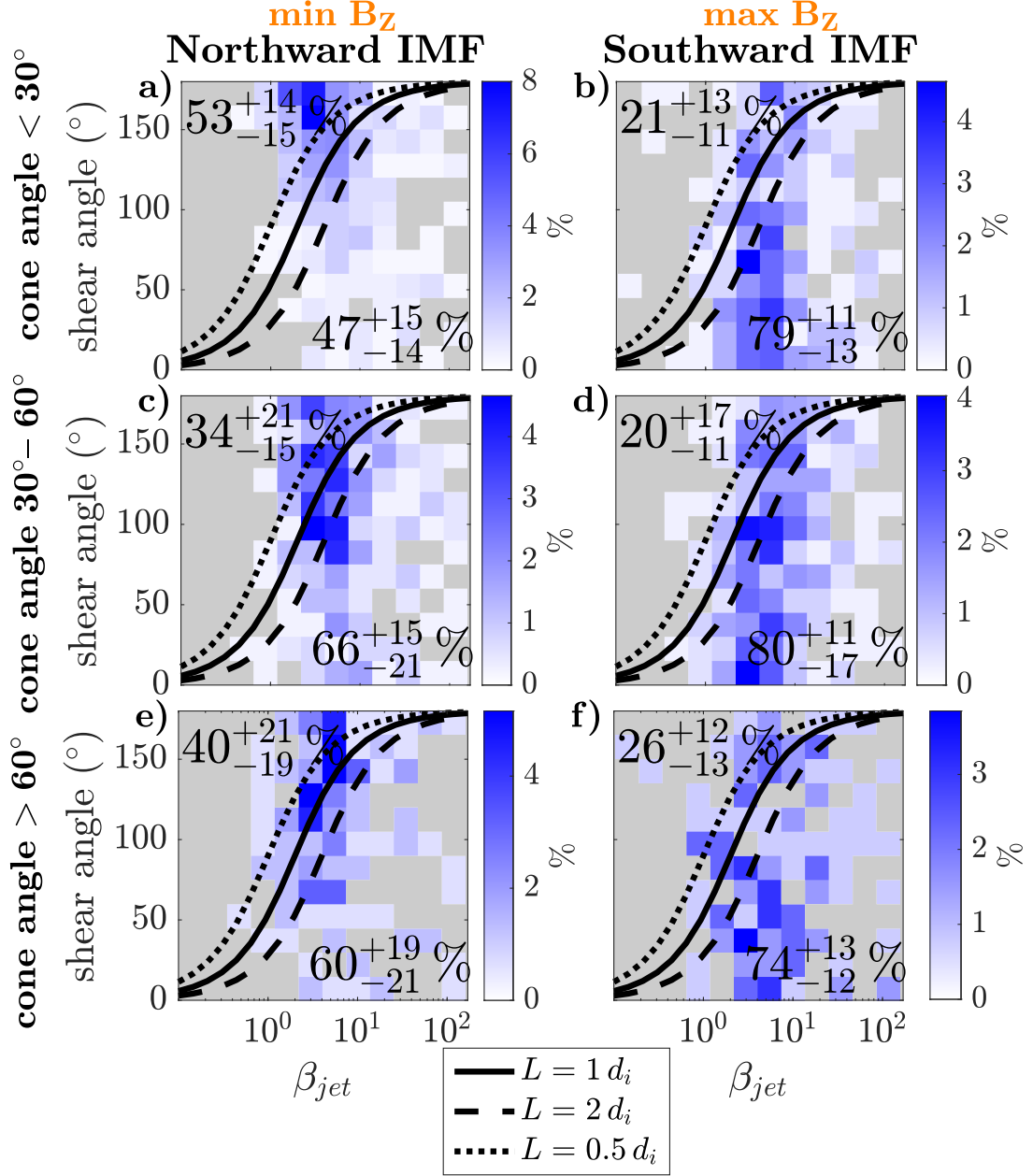
**Figure 4.7:**  $\beta$ -shear plots for near-magnetopause jets. All data determined to be within a jet interval are shown. Same format as Figure 4.6.

angle in the same format as Figure 4.6. The data shown are all those deemed to be within jet intervals. Here we can clearly see the effect of increased jet  $\beta$ , by the grey region on the left of each panel (low  $\beta$  side), which indicates an absence of data. This means that in every case, the majority of data are in the reconnection-suppressed zone, even during times of southward IMF. It seems, therefore, that the effect of increased  $\beta$  is greater than the tendency of jets to exhibit intervals of  $B_Z$  oppositely directed to the IMF direction (Vuorinen et al., 2021) in the competition for reconnection suppression, making jet plasma generally more likely to suppress reconnection than trigger it, even more so than the non-jet magnetosheath. Here we do not see the monotonic dependence on cone angle observed for non-jets, with the proportion of reconnection favourable plasma similar for each of the three cone angle brackets.

Pooling all jet data together, as in Figure 4.7, does not necessarily show the whole picture. While it may lead us to conclude that the majority of jet plasma is not favourable to reconnection, it does not tell us how often any given jet may contain some reconnection favourable plasma. To address this, we present Figure 4.8. Motivated by the methods of Vuorinen et al. (2021), we study the extremes of each jet interval to assess the ability of jets to modify reconnection from what would be expected from the IMF orientation. We do this by selecting moments of  $B_Z$  minima and maxima from each jet interval, and plotting against the corresponding  $\beta$ . For jet intervals observed during northward IMF, we select the moment of minimum  $B_Z$  to assess the likelihood that a jet may be able to trigger reconnection. Similarly, during times of southward IMF we select the maximum  $B_Z$  from each jet interval to assess the ability of a jet to suppress ongoing reconnection at the magnetopause.

Comparing Figures 4.7 and 4.8 we see, as expected, an increase in the proportion for which reconnection may be altered from the IMF expectation. That is to say, a greater proportion of events determined to be suitable for reconnection during northward IMF, and expected to suppress reconnection during southward IMF. Across all cone angles, we find that during northward IMF  $43^{+18}_{-16}$  % of jets contain at least one moment





**Figure 4.8:**  $\beta$ -shear plots for extreme points within jets. Same format as Figures 4.6 and 4.7, however the observations under northward IMF show only the properties at the moment of minimum  $B_z$  within each jet interval, and the southward IMF observations represent the moment of maximum  $B_z$  within each jet interval.

where the conditions are such that reconnection may be allowed. This is over twice the corresponding fraction for all jet plasma. During southward IMF,  $79^{+11}_{-15}$  % of jets contain a moment where reconnection would be expected to be suppressed, 24 % higher than for all jet plasma.

It is clear that reconnection suppression is still dominant, even when selecting the extremes of each jet interval. However it is notable that approximately half of the jets we observed near the magnetopause could trigger reconnection during times of northward IMF. This effect is strongest during low IMF cone angle solar wind (Figure 4.8), which is also the condition under which jets are most likely to form and reach the magnetopause (as established in the previous chapter).

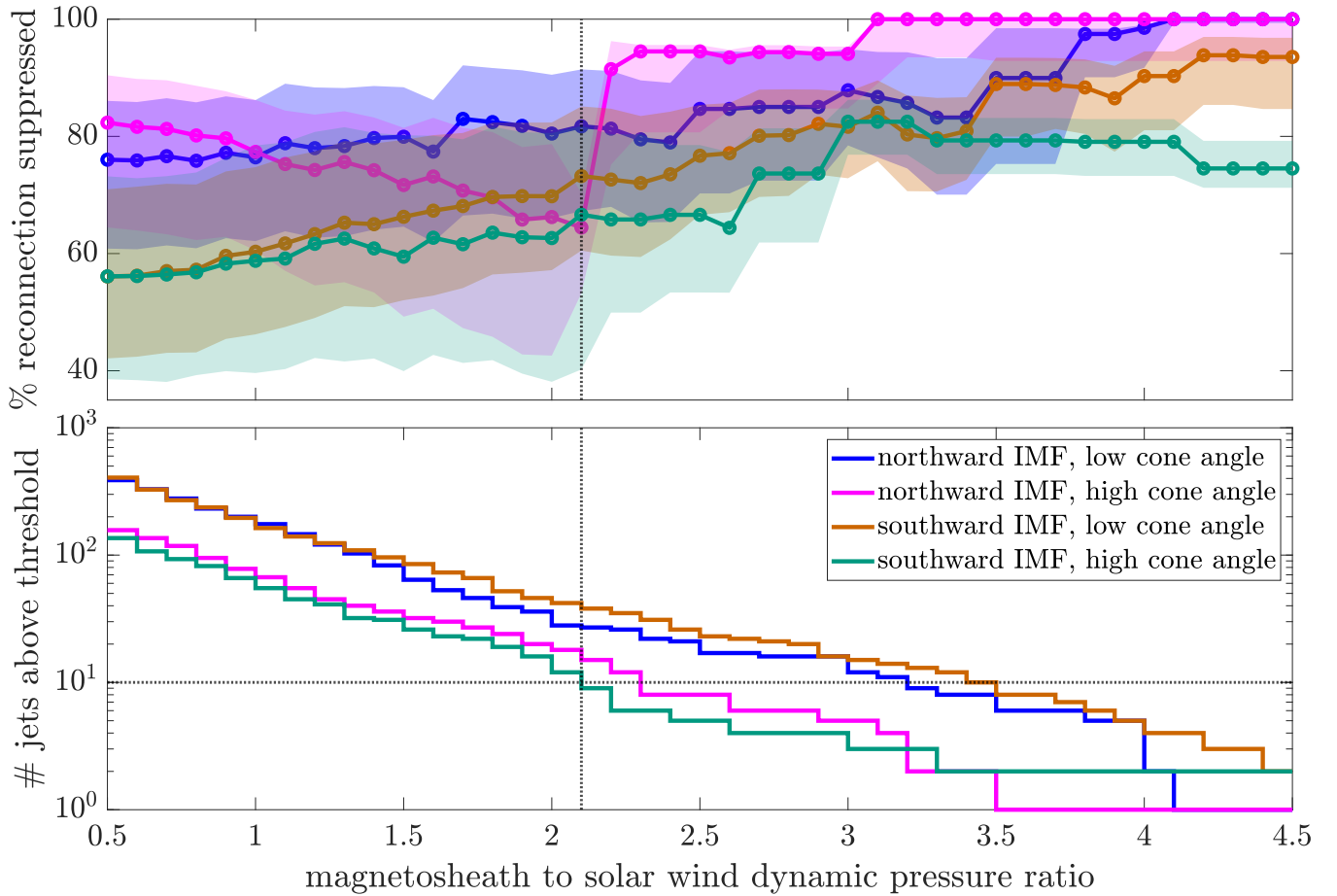
Jets have previously been seen to trigger reconnection by virtue of their increased dynamic pressure compressing the magnetopause layer (Hietala et al., 2018). Therefore, jets with the highest dynamic pressure enhancements are of significant interest, as they are perhaps the most likely to be geoeffective. We therefore find it pertinent to study the  $\beta$ -shear properties of jets with high dynamic pressure enhancements. We do this by isolating jets whose maximum magnetosheath to solar wind dynamic pressure ratios exceed certain thresholds. For jets that exceed the threshold, we include all plasma contained within that jet interval, and calculate the proportion that would suppress reconnection, as before.

In Figure 4.9 we show the calculated percentage of reconnection suppression as a function of magnetosheath to solar wind dynamic pressure ratio, separated by various IMF conditions. Note that the minimum value of this ratio is 0.5, which is the threshold for jet identification. We see, with increasing magnetosheath to solar wind dynamic pressure ratio, an increase in the proportion of plasma contained within jet intervals that would be expected to suppress reconnection. This trend is consistent between all the IMF conditions tested, with the exception of jets observed during northward IMF with a high cone angle, which initially shows a decrease (i.e., increasing the proportion of jet plasma favourable to reconnection), before reversing the trend after a pressure

ratio of around 2.

As can be seen in the lower panel of Figure 4.9, the number of jets included in the statistics drops off rapidly at high dynamic pressure ratios. Beyond a magnetosheath to solar wind dynamic pressure ratio of 2.1, there are fewer than 10 jets considered in the southward IMF, high cone angle category. At ratios of 3.5 and above fewer than 10 individual jets are included in each of the four solar wind categories, though it is worth noting that the entirety of the plasma from each jet interval is considered when calculating the proportion expected to suppress reconnection, and so this still represents a significant quantity of plasma measurements.

From this we find the perhaps surprising conclusion that jets with the highest dynamic pressure ratios, which would be expected to have the most significant impact on the magnetopause, are the least likely to trigger reconnection (based on their  $\beta$ -shear characteristics). When examining some examples of jets with particularly high dynamic pressure ratios, we find that they are often strongly density driven, leading to a particularly high  $\beta$  at the magnetopause, and thus increasing the likelihood of reconnection-suppressive plasma.



**Figure 4.9:** Change in proportion of jet plasma predicted to suppress reconnection with increasing jet magnetosheath to solar wind dynamic pressure ratio measured at  $t_0$ , for different IMF orientations. Top panel: markers and line show the % calculated assuming  $L = 1 d_i$ , while the shaded regions denote the uncertainty range between  $L = 2 d_i$  and  $L = 0.5 d_i$ . Bottom panel: survivor distribution showing the number of jets above each threshold point. Dashed lines mark the point at which fewer than ten jets contribute to the statistics.

## 4.4 Discussion and conclusion

We have studied the typical properties of jets in the magnetosheath, both near the bow shock and at the magnetopause. We expect that these are useful for the community, particularly as input parameters for jets in simulations. By separately studying the properties of jets at the bow shock and magnetopause, we provide inputs to study the evolution of typical jets from the bow shock, as well as the effects arising from their properties at the magnetopause. Not making this distinction would be an oversimplification, as we have seen that jet properties may differ between these regions. While we may infer details of the ways in which jet properties evolve through propagation, we cannot make conclusions without support from multi-spacecraft studies and simulations that are able to track individual jets. It may also be the case that we see the effects of filtering through the magnetosheath, i.e., which kinds of jets are most likely to survive to the magnetopause. We suggest for future study that connections can be made between the properties of jets at the magnetopause and the solar wind conditions under which they are observed.

By comparing typical jet properties with the non-jet magnetosheath, we can learn about how they may interact with their surroundings. In Figure 4.3, we see that in thermal, magnetic, and dynamic pressure components, there is a greater disparity between jets and the magnetosheath at large at the magnetopause than at the bow shock. This is perhaps demonstrative of the ways in which jets may disperse during propagation, as they become more susceptible to instabilities. It should be noted, however, that the non-jet magnetosheath on average is not necessarily representative of the surrounding magnetosheath plasma during jet impacts, as (based on the results in the previous chapter), we know that particular solar wind conditions are required. We therefore suggest for future study an analysis of pre-and post-jet intervals as a proxy for the surrounding plasma, compared at different stages of propagation.

A key result was establishing the competition of jet  $B_z$  oppositely directed to the IMF and the increased  $\beta$  compared to the magnetosheath on average at the magnetopause,

creating a potential conflict in the  $\beta$ -shear condition for reconnection, which prompted further investigation. In Figure 4.6, we parameterised 11 years of near-magnetopause plasma and determined the proportions for which reconnection would be expected to be allowed or suppressed. To the best of our knowledge, this is the first time that such an analysis has been performed. As well as serving as a validation of our methods, this enhances our understanding of typical magnetosheath behaviour in the subsolar region. It is interesting to note that, while broadly supportive of the global picture arising from IMF orientation, the percentages are not as clear-cut as one might expect. This information may be useful for forecasting regimes, e.g., knowing that during southward IMF the conditions required for reconnection are only fulfilled approximately 60 % of the time.

We then compared these values with those seen from all plasma within jet intervals (Figure 4.7), finding jets to be more suppressive than the non-jet magnetosheath under all IMF orientations, due to their enhanced  $\beta$ . This means that even during southward IMF, less than half of the plasma within jet intervals would be expected to allow reconnection. There did not appear to be a strong influence of cone angle on these statistics. However, when restricting to  $B_z$  extremes within each jet interval, we saw that the fraction of jets with some reconnection-allowed plasma during northward IMF increase. Suggesting that reconnection may be possible on a localised level, depending on the timescales required.

It seems that, despite possessing higher  $\beta$  plasma than the magnetosheath on average, they have the potential to modify reconnection from what would traditionally be expected based on upstream measurements of the IMF orientation. This would suggest that we require more than simple measurements of the IMF orientation at L1 in order to predict the magnetopause response. Jets may provide an internal source or suppressor of localised magnetopause reconnection that is not well-predicted by the  $B_z$  at L1. In some cases jet impacts may contribute flux loading that leads to substorm onset, as was observed by Nykyri et al. (2019). The fluctuating and impulsive nature of jets perhaps

lends itself more to bursty localised reconnection than global effects. In a statistical study of FTEs at the magnetopause, Kullen et al. (2019) found that 16 % of isolated FTEs were associated with low cone angle, quasi-radial IMF. They suggested that these may therefore be related to the impact of jets. Our results are supportive of this idea. However our statistics suggest that jets are more likely to suppress reconnection than trigger it, meaning the magnetospheric dynamics stimulated by southward IMF may be moderated by the presence of jets, particularly if the solar wind conditions are such that jets arrive at the magnetopause in high numbers (e.g., low cone angle, high solar wind speed). This is a new and interesting result that somewhat goes against the typical paradigm, perhaps arising from a bias towards reporting observations and simulations where jets have been linked to reconnection triggering but not suppression.

By studying the proportion of reconnection-suppressive plasma as a function of magnetosheath dynamic pressure (Figure 4.9), we established that the jets with highest dynamic pressures, which would traditionally be considered to be the most geoeffective, are also the most likely to be entirely dominated by reconnection-suppressing plasma by virtue of their high densities and therefore high  $\beta$ . That is not to say that these jets would not be geoeffective, but it may be the case that the effects arising from the pressure pulse exerted on the magnetopause may outweigh those from reconnection.

Our analysis is subject to several caveats and limitations. As described in Section 4.2.1, our predictions of reconnection behaviour are based on a series of assumptions. These stem from not having near-simultaneous measurements on both sides of the magnetopause in every case. Our assumption that the magnetopause field is directed purely in the positive GSM-Z direction is likely well-justified on broad scales, given that we work exclusively in the subsolar region. However this is perhaps not well-justified on localised scales, particularly given that we know jet impacts can indent and compress the magnetopause (e.g., Shue et al., 2009; Hietala et al., 2018). Similarly, we assume  $\beta$  inside the magnetosphere to be negligible in comparison to that of the magnetosheath. This means that our predictions are likely to be skewed somewhat to

the side of reconnection suppression, though the extent of this bias is considered to be well-within the error range arising from the variation of current sheet width.

Our analysis hinges on comparing in situ measurements in the magnetosheath with simultaneous upstream solar wind conditions as provided by the OMNI database (King and Papitashvili, 2005). However it is known that the spatial variation of the solar wind and structures contained within can occasionally cause OMNI to be an unreliable predictor of the solar wind conditions arriving at Earth (e.g., Borovsky, 2018; Ala-Lahti et al., 2021). While our studies will inevitably contain some cases where the true IMF orientation at the bow shock differs from the OMNI value, we aim to minimise the effect of this by drawing conclusions only from large data sets.

While our statistics allow us to make useful predictions for the likely  $\beta$ -shear conditions jets bring to the magnetopause, we cannot predict exactly how the magnetopause will respond. An open question in the study of reconnection concerns the timescales over which it occurs. Specifically, how long are conditions at the magnetopause required to be favourable to trigger reconnection onset? We have seen that the magnetic field signatures of jets are typically highly variable, meaning prolonged intervals of consistent  $B_z$  are rare. If a greater degree of stability is required for reconnection onset, then jets may have a great suppressive effect on quasi-steady reconnection. It is also possible that the more important factor in determining a jet's role in reconnection is whether its dynamic pressure is sufficiently enhanced so that the magnetopause layer is compressed enough to reconnect. Further study is needed to examine whether the magnetopause responds as expected following a jet impact. In the next chapter we aim to do this through case study analysis.

We will go on to show that the  $\Delta\beta$ -shear condition does not accurately predict reconnection at the magnetopause in the case study. The possible reasons for this include the magnetopause being extremely dynamic in response to several large jet impacts in a short time interval, with localised deformations complicating the geometry. We also find evidence for the presence of a plasmaspheric drainage plume, which adds uncer-



tainty to direct calculation of  $\Delta\beta$  at the magnetopause. This in mind, we acknowledge that there may be limitations to using the relation to predict reconnection in instances of jets impacting the magnetopause, compared to the quasi-steady conditions for which it has been shown to perform well in previous literature. While an important caveat, it does not, however, invalidate the studies presented in this chapter. Here we study only magnetosheath plasma, particularly that contained within jet. In this sense, we are able to make predictions for the possible influence these plasma parcels may have on reconnection at the magnetopause, in the absence of any knowledge about the magnetopause itself. Given the proven merit of the  $\Delta\beta$ -shear relation, we can be confident that there is value in using it to understand how jet plasma may influence reconnection on an idealised magnetopause.

## Chapter 5

# Local Magnetopause Reconnection and Dynamics Following Jet Impacts

### 5.1 Introduction

In the previous chapter we performed a statistical study on the properties of jets near the magnetopause and made predictions for how they may modify localised reconnection based on their  $\beta$ -shear properties. We found that the increased  $\beta$  of jet plasma makes them more likely to suppress reconnection that trigger it, but also that their magnetic fields are sufficiently variable such that most jets contain at least one plasma parcel with  $\beta$ -shear conditions that could modify reconnection from what would be expected from the IMF orientation observed upstream.

To date, there has only been one study to directly observe a jet triggering reconnection, which was that of Hietala et al. (2018). Other studies, such as that by Nykyri et al. (2019) have indirectly inferred jets contributing to flux loading in the magnetotail via reconnection at the magnetopause. Multiple simulation studies have also linked jets with bursty reconnection at the magnetopause and the formation of FTEs (Karimabadi et al., 2014; Ng et al., 2021). Our results in the previous chapter, however, indicate that

the role of jets in magnetopause reconnection is likely to be complicated, with both triggering and suppressive effects possible. To the best of our knowledge, no previous studies have specifically examined reconnection suppression by jets.

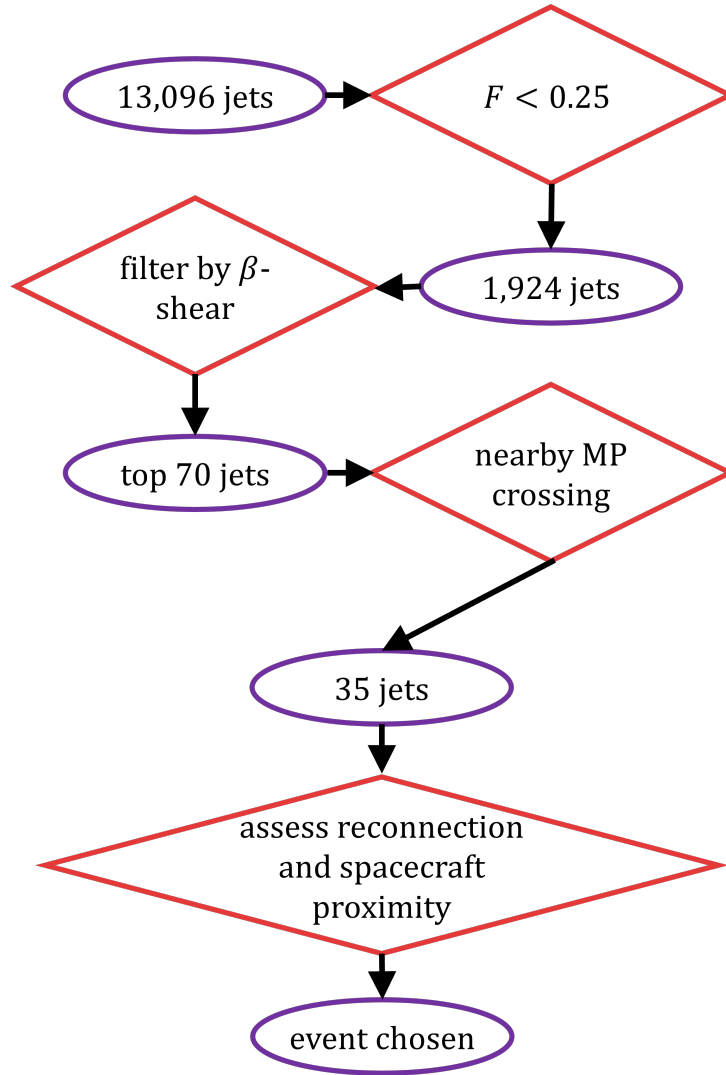
In this chapter we present a multi-spacecraft case study of multiple jets impacting the magnetopause in quick succession to further our understanding of the role they play in magnetic reconnection, and test the predictions made in Chapter 4. We will go on to show that jets play an important role in bursty reconnection, producing highly localised effects on an extremely dynamic magnetopause. While not an exhaustive examination of a complex event, our study serves as a demonstration of analysis techniques required to understand jets and their role in local reconnection and magnetopause dynamics. We make several suggestions for future avenues of investigation, both for this particular case study and beyond.

## 5.2 Methods and analysis tools

### 5.2.1 Event selection and database

The process undertaken to select an event for the case study is illustrated in Figure 5.1. To find interesting events for the objectives of this study, the jet database was filtered according to several criteria. In order to find instances of jets impacting the magnetopause we only considered events with  $F < 0.25$ . Jet observations were ranked according to their likelihood of modifying reconnection from the IMF-based expectation, based on the shear angle and  $\Delta\beta$  estimates used in the previous chapter. The top 70 events satisfying these criteria were visually inspected to identify magnetopause crossings close to jet observations. 35 of the 70 were found to have a magnetopause crossing within 5 minutes of a jet observation. These events were then assessed for proximity of other THEMIS spacecraft, with priority given to those with small separation between probes.

The interval selected for study here was chosen on the basis of its complexity, with multiple jet observations and magnetopause crossings made by spacecraft across the



**Figure 5.1:** Flow chart illustrating the process undertaken to select a case study event.

magnetopause (more information in Section 5.3), making it ideal for the development of analysis techniques. It is, however, not a unique event. We therefore expect that the tools applied and observations made can be extended to many other scenarios, both in our jet data base and beyond.

### 5.2.2 Hybrid minimum variance analysis

At each magnetopause crossing, hybrid minimum variance analysis (HMVA) is applied (see, e.g., Gosling and Phan, 2013; Mistry et al., 2017; Eastwood et al., 2018). This technique is described in more detail in Section 2.3.3. The HMVA interval boundaries are initially selected by visual inspection and later adjusted to maximise the intermediate to minimum eigenvalue ratio. By doing this we are able to recast each magnetopause

crossing into a coordinate system that accentuates the field rotation and exhaust in the L-direction.

Figure 5.2 shows a time series plot of one of the magnetopause crossings in the case study event, which illustrates some of our analysis techniques applied to every magnetopause crossing. HMVA has been performed using the the magnetic field vectors at the points marked by black vertical dashed lines either side of the current sheet. Using this, the magnetic field (Figure 5.2b) and ion velocity (Figure 5.2h) components are transformed into an LMN coordinate system.

### 5.2.3 $\Delta\beta$ and shear angle

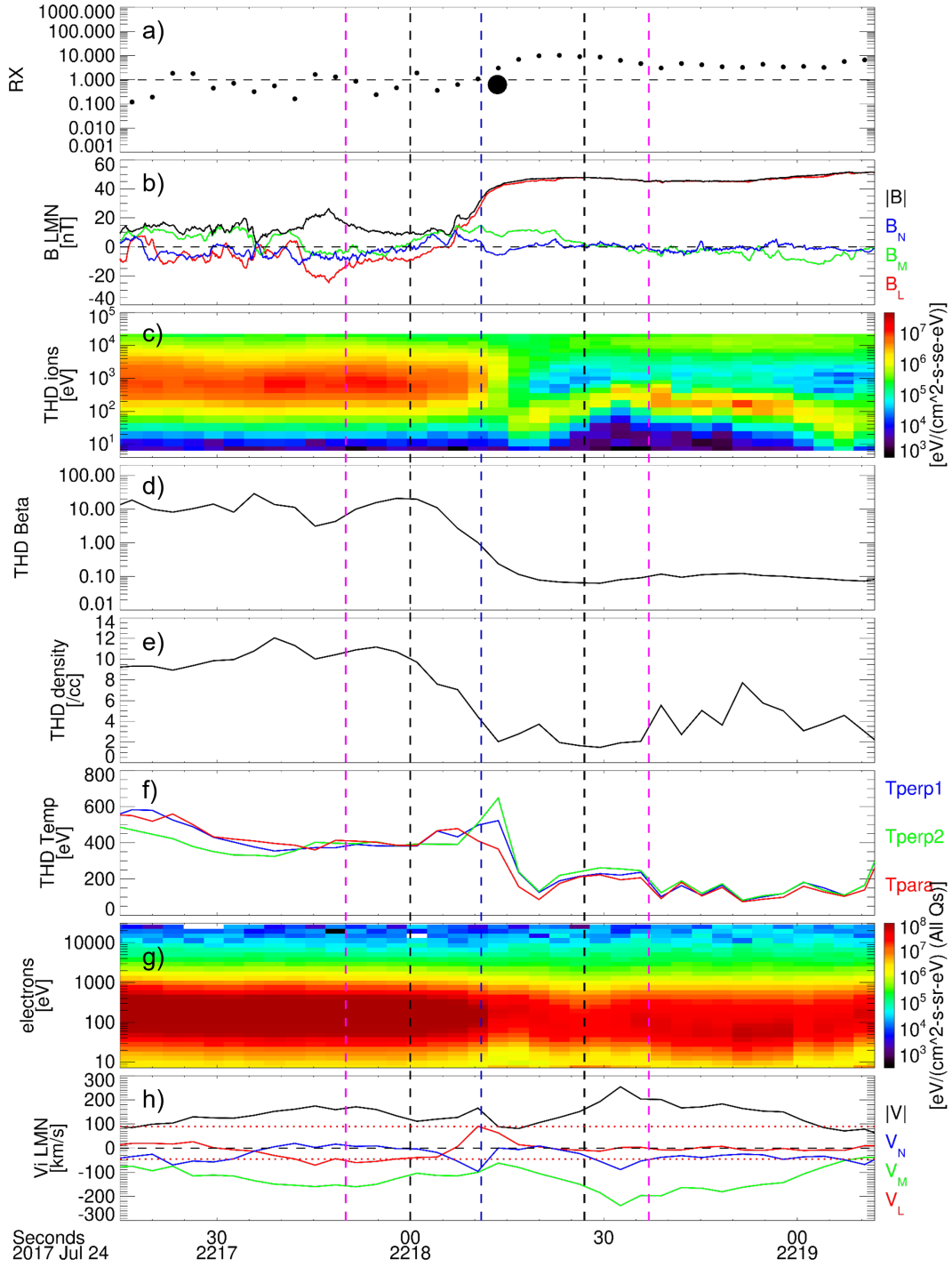
We wish to apply the  $\Delta\beta$ -shear relation (Eq 1.9) at magnetopause crossings in the case study event. In order to quantify the degree to which reconnection is favourable, we can take the ratio of the terms in the relation. We therefore define

$$R_X = \frac{2 \tan(\theta/2)}{\Delta\beta}, \quad (5.1)$$

which assumes a current sheet width of  $L = 1 d_i$ . Reconnection is allowed when  $R_X > 1$ , and suppressed when  $R_X < 1$ . The smaller the value of  $R_X$ , the stronger the expected suppression by diamagnetic X-line drift.

Unlike in the previous chapter, where  $\Delta\beta$  and shear angle parameters were estimated based solely on the magnetosheath conditions close to the magnetopause, here we can calculate them directly from each magnetopause crossing.  $\Delta\beta$  is therefore given by the difference in  $\beta$  each side of the magnetopause, and the shear angle is the angle between the magnetic field vectors. For both we take a 10-second average of the properties either side of the HMVA interval times. This is in line with the methods of Phan et al. (2013).

For comparison, we also estimate  $R_X$  using the methods outlined in Chapter 4. That is to say, we use the magnetosheath  $\beta$  as a proxy for  $\Delta\beta$  and estimate shear angle by calculating the angle between the magnetosheath magnetic field and the GSM-Z axis.



**Figure 5.2:** Magnetopause crossing time series illustrating analysis techniques. a) reconnection favourability ( $R_X$ ); b) magnetic field in LMN coordinates; c) ion spectrogram; d)  $\beta$ ; e) density; f) temperature, perpendicular and parallel components; g) electron spectrogram; h) ion velocity in LMN coordinates. Black vertical dashed lines mark the points either side of the current sheet used to perform HMVA. Magenta vertical dashed lines mark the outer edges of 10 second intervals over which properties are averaged to estimate  $\Delta\beta$ , magnetic shear, and  $V_{AL,asym}$ . Blue vertical dashed line marks the point in time of maximum  $V_L$  enhancement between the black dashed lines. In panel h), red dashed lines mark the value of maximum  $V_L$  enhancement and background flow value used to calculate  $\Delta V_L$ .

This enables us to predict the reconnection favourability of each plasma parcel in the magnetosheath, upon propagation to the magnetopause. Note that this is meaningless for plasma inside the magnetosphere.

Figure 5.2a shows the two methods of calculating  $R_X$  for this example magnetopause crossing. The small dots show our continuous estimate of  $R_X$  using the methods of Chapter 4. We can see that in the magnetosheath section (left side of the plot), the value of  $R_X$  is quite variable, due to the fluctuating magnetic field and  $\beta$  in that region. In the magnetosheath region before the first magenta dashed line),  $R_X \ll 1$ . This is due to the enhanced  $\beta$  ( $\sim 30$ ) making reconnection unfavourable despite the relatively large shear angle. However, immediately in front of the magnetopause (where  $B_L$  begins to rotate),  $\beta$  drops and the metric indicates that the plasma is reconnection favourable. The large dot shows the value of  $R_X$  calculated directly from the shear angle and  $\Delta\beta$  across the magnetopause, using averages of the conditions 10 seconds either side of HMVA times. These regions are bounded by the magenta dashed lines in Figure 5.2. At a value of 0.63, this indicates that reconnection is expected to be suppressed at this magnetopause site. Despite this, we do observe a reconnection signature at this crossing. The possible reasons for this are discussed in Section 5.4.

### 5.2.4 Outflow speed

Reconnection at the magnetopause is typically highly asymmetric due to the disparity in density and magnetic field strength either side of the magnetopause current sheet. Under these conditions, the reconnection exhaust speed is expected to be similar to the asymmetric Alfvén speed, given by

$$V_{\text{AL,asym}} = \sqrt{\frac{B_{1L}B_{2L}(B_{1L} + B_{2L})}{\mu_0(\rho_1 B_{2L} + \rho_2 B_{1L})}} \quad (5.2)$$

where subscripts 1 and 2 refer to the two reconnecting plasma populations (in this case, magnetosphere and magnetosheath), and subscript L denotes the MVA-L components of the relevant magnetic fields (Cassak and Shay, 2007; Swisdak and Drake, 2007;

Eastwood et al., 2013; Hietala et al., 2017). Note that for symmetric inflow conditions ( $B_{1L} = B_{2L}$  and  $\rho_1 = \rho_2$ ), this simplifies to the regular Alfvén speed (Eq 1.2). It has been noted, however, (e.g., by Hietala et al., 2017) that Eq 5.2 tends to over-predict exhaust speeds, and those observed by spacecraft are almost always sub-Alfvénic.

We use this information in our assessment of reconnection, by comparing observed outflow speeds with the asymmetric Alfvén speed for each magnetopause crossing. To estimate a value for  $V_{AL,asym}$  at each magnetopause crossing, we average the magnetic field and density properties for 10 seconds either side of the defined HMVA interval. In some instances, however, where there is a large degree of variation in these properties (particularly magnetic field) in this window, we reduce the window size and use only the measured values closest to the HMVA interval points. This is adjusted on a case by case basis.

In order to characterise exhaust speeds, we find the maximum L-directed velocity enhancement ( $\Delta V_L$ ) within or close to the HMVA interval. In instances where there is a significant degree of background flow remaining in the LMN velocity, we estimate this based on the nearby magnetosheath flow and calculate  $\Delta V_L$  relative to this. This effectively calculates the exhaust velocity enhancement in the near-magnetopause solar wind frame. This is illustrated by the red dashed horizontal lines in Figure 5.2h, which mark the  $V_L$  exhaust enhancement as well as the magnetosheath background, thus defining  $\Delta V_L$ . In order to confirm a suspected reconnection exhaust, we require the estimated  $\Delta V_L$  to be over 40 % of the estimated asymmetric Alfvén speed.

As detailed in Section 1.3, the asymmetry of inflow conditions at the magnetopause has several effects on the reconnection geometry. One of these is that the maximum velocity enhancement within an exhaust is typically expected to be observed closer to the low density side, i.e., the magnetosphere (Eastwood et al., 2013). While not the most significant criterion applied, we take this expectation into consideration when making a judgement on a potential reconnection signature. This is demonstrated in Figure 5.2 by the dashed blue line, which marks the velocity peak of the exhaust. We can see that



it is observed closer to the magnetosphere than magnetosheath field, in line with the observations of Phan et al. (1996) who reported velocity peaks 89 % of the way through magnetosheath to magnetosphere field rotation, and at a density drop of 66 %.

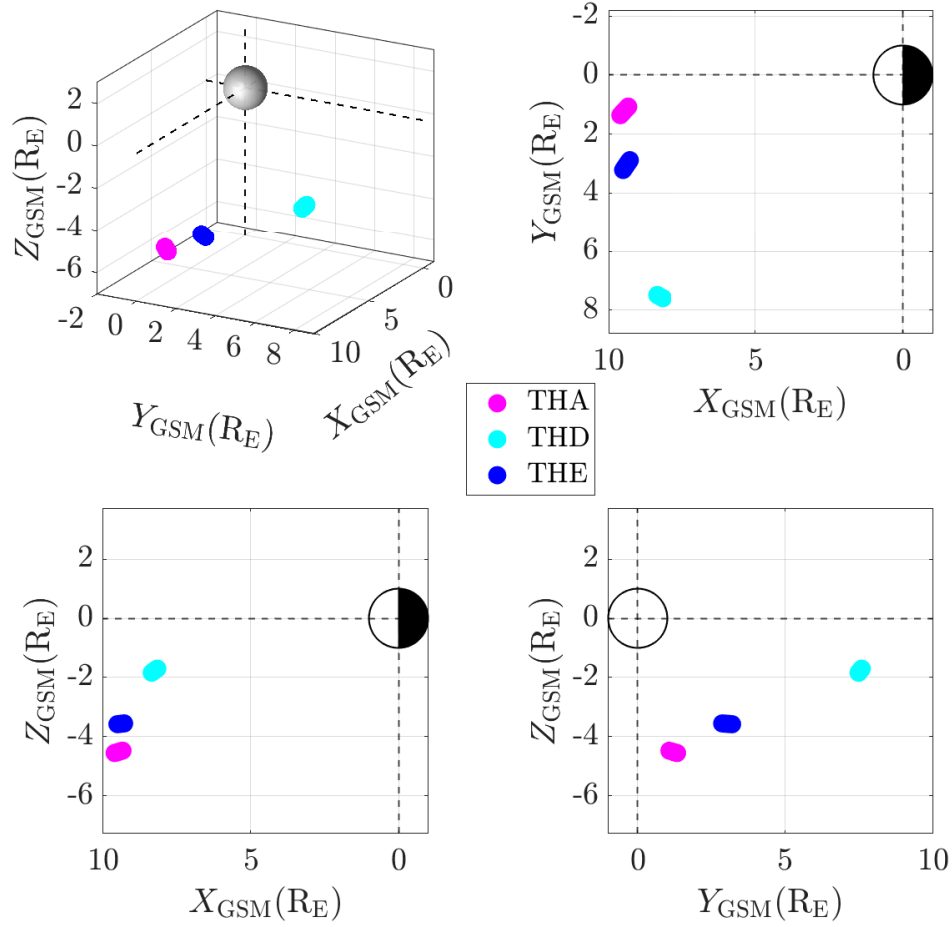
## 5.3 Case study: July 24<sup>th</sup>, 2017

### 5.3.1 Event overview

The event chosen was seen by THEMIS on 24<sup>th</sup> July 2017 at around 22:00 UTC. The IMF according to OMNI during this period was weakly southward with a strong X-directed component, making it nearly radial with an average cone angle of around 30°. This means that, as established in Chapter 3, the conditions were good for many jets to form and reach the magnetopause.

Figure 5.3 shows the spacecraft positions throughout the interval. THEMIS probes A, D, and E were positioned nearby to each other at the magnetopause. All three were in the dusk sector (positive  $Y_{GSM}$ ) and below the equator (negative  $Z_{GSM}$ ). THA and THE were particularly close to each other with a mean separation of 2.1  $R_E$ . THD was positioned further out, closer to the magnetic equator in the Z-direction as well as further duskward, 5.0  $R_E$  from THE, and 7.0  $R_E$  from THA.

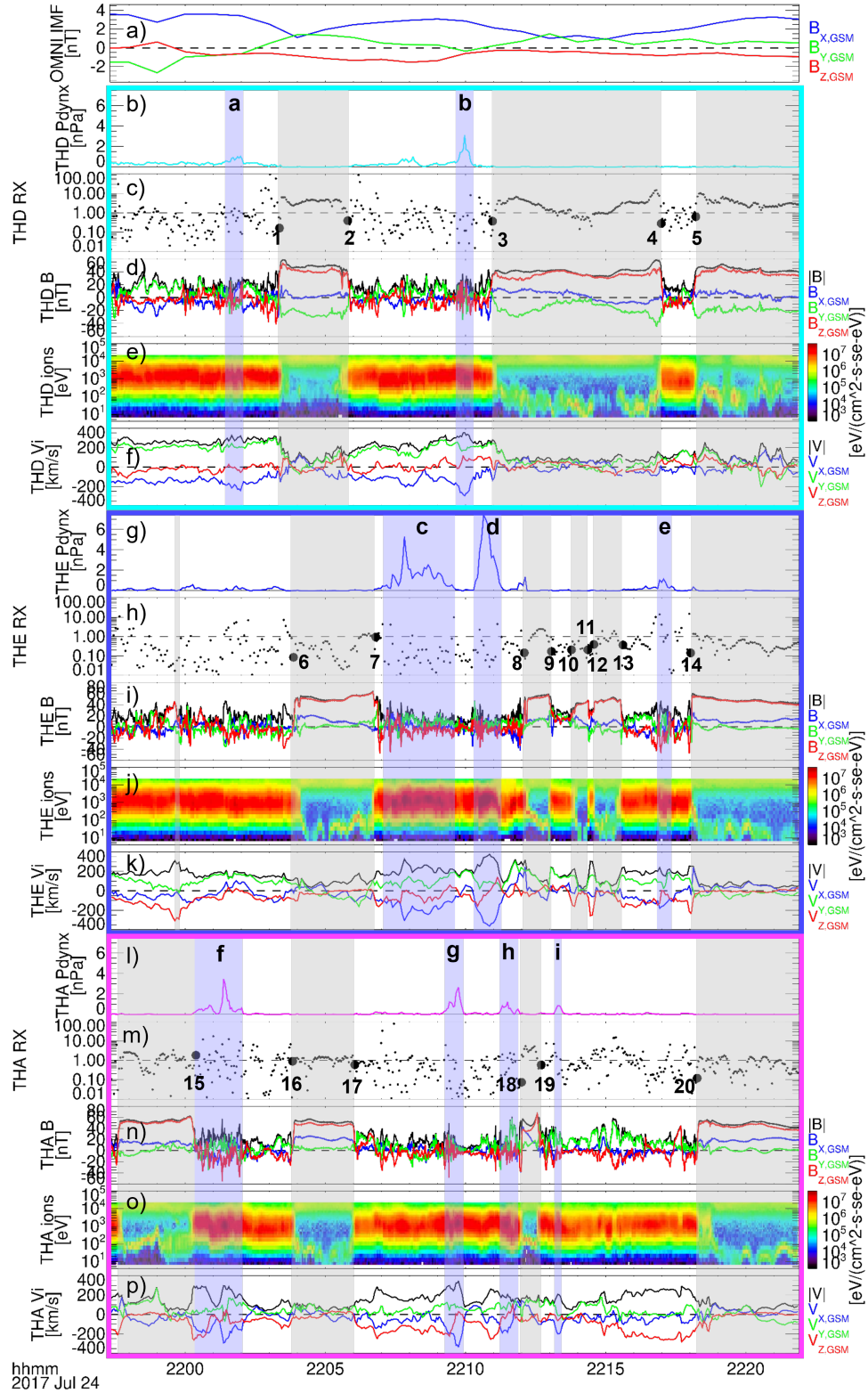
Figure 5.4 shows the in situ measurements made by each of the three THEMIS probes during the interval, as well as the IMF seen by OMNI, time lagged by 5 minutes. The plot is arranged according to the spacecraft  $Z_{GSM}$  coordinates, i.e., with THD at the top, followed by THE then THA. During the 25 minute event window, the THEMIS probes observed 9 jets between them: 2 by THD, 3 by THE, and 4 by THA. These are shaded in blue in Figure 5.4 and labelled by letters a)–i). The jet that lead to the selection of this event was jet g). Not all of the surrounding jets are included in the jet database due to the requirement for 1 minute continuous magnetosheath intervals either side of the jet. Those shaded in blue, however, are found to satisfy the dynamic pressure criteria of Plaschke et al. (2013). The jets had an average maximum dynamic pressure of 2.9 nPa,



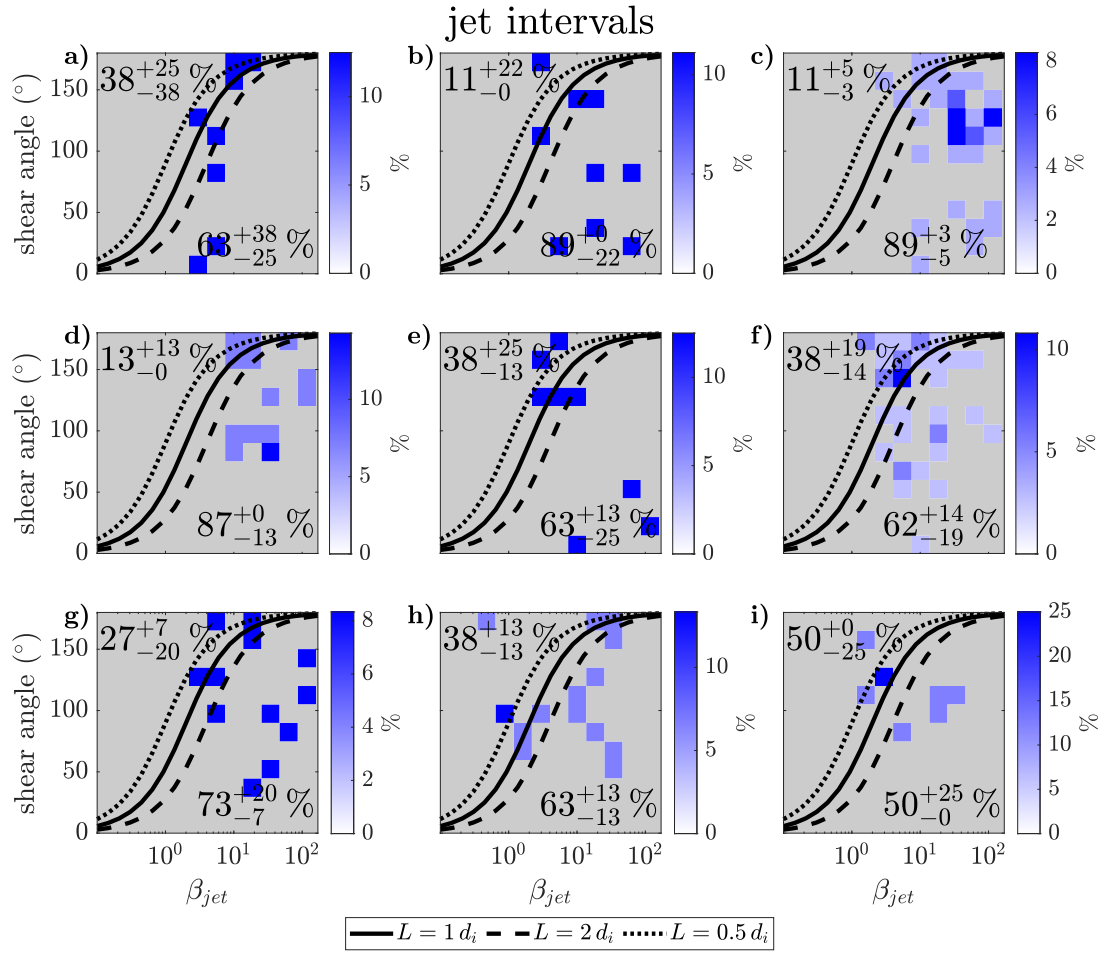
**Figure 5.3:** THEMIS spacecraft positions (in GSM) during the 24<sup>th</sup> July 2017 case study event. All three probes were situated in the dusk sector, below the equator on the dayside.

with two of those seen by THE being particularly strong, at 5.3 and 7.4 nPa, the latter of which is in the top 2 % of the jet database.

During the interval, the magnetopause was highly dynamic, as evidenced by the repeated magnetopause crossings seen by the spacecraft. Times in which a spacecraft was inside the magnetosphere are depicted by grey shaded regions in Figure 5.4. Each of these magnetopause crossings are studied and assessed for their reconnection signatures, as described in Section 5.2 and Figure 5.2. Those under study are numbered 1–20 in Figure 5.4. For each spacecraft we calculate  $R_X$  in both of the ways described above.



**Figure 5.4:** Overview plot of case study event on July 24<sup>th</sup> 2017. Panel a) shows magnetic field (GSM) as seen by OMNI, time-lagged by five minutes. Panels b)–f) show THEMIS D observations (cyan box), panels g)–k) show THEMIS E observations (blue box), panels l)–p) show THEMIS A observations (magenta box). For each spacecraft, the data shown are (top to bottom): dynamic pressure,  $R_X$  (see text), magnetic field (GSM), ion spectrogram, ion velocity (GSM). Blue shaded regions denote jet intervals, while grey regions show when a spacecraft was inside the magnetosphere. Magnetopause crossings studied are numbered, and jets are labelled with letters.



**Figure 5.5:** 2D histograms showing  $\beta$ -shear estimates for jets considered in the case study. Magnetic shear angle and  $\beta$  are estimated using the same methodology as described in Chapter 4. Labels a)–i) correspond to the jets labelled in Figure 5.4.

Large circles indicate the value calculated at each magnetopause crossing by using the  $\Delta\beta$  and shear angle directly, while the small circles show the continuous estimate for all plasma parcels in the magnetosheath.

### 5.3.2 $\beta$ -shear properties of jets

To make connection with the statistical techniques applied in the previous chapter, we estimate the  $\beta$ -shear properties of jets in the case study event. For each of the nine jets observed across the three spacecraft, we calculate the  $\beta$  of all plasma within each jet interval and use this as a proxy for the  $\Delta\beta$ . We also estimate the magnetic shear angle these plasma parcels would make with the magnetopause by calculating the angle to

the GSM-Z axis, as was done in the previous chapter. Placing these observations in the  $\beta$ -shear parameter space, we produce Figure 5.5. Panels a)–i) correspond to the labels on jet intervals in Figure 5.4. As before, data in the top left of each histogram are those representing plasma for which reconnection is allowed, while the bottom-right region is where reconnection is expected to be suppressed.

In agreement with the results of Chapter 4, most jet plasma lies in the suppressive region of the parameter space. Across the nine jets, the average proportion of suppressive plasma (at the  $L = 1 d_i$  threshold) is 72 %. The jet with the highest proportion of reconnection-favourable plasma contained within its boundaries is jet i), seen by THA, at 50 %. The dominance of suppressive qualities appears to be driven primarily by the enhanced  $\beta$  rather than low shear angle. Most jets in this interval exhibit a range of shear angles. A notable example is jet e), which includes plasma across the whole range of shear angles, with particularly high concentrations near 0 and 180 degrees. Jet g) also shows a reasonable spread of shear angles, though with a flatter distribution. In general, they skew towards high shear, antiparallel formation. This was confirmed in 1D histograms in shear angle (not shown). Not all the jets are so spread, such as jets d), and i), which exhibit a clear clustering in the parameter space. In demonstration of the later results of Chapter 4, we can see that the variability within jet intervals means that almost all of them do contain some amount of reconnection favourable plasma.

### 5.3.3 Magnetopause crossings and reconnection signatures

Table 5.1 lists key details for each of the magnetopause crossings studied. The values of  $R_X$  indicate the whether reconnection is to allowed, based on the  $\Delta\beta$  and shear angle calculated at each crossing using the methods described above. In Table 5.1, the ‘exhaust’ column indicates whether a reconnection signature was observed.

Reconnection exhausts were seen at 11 of the 20 magnetopause crossings, 5 were determined to not be reconnecting, and 4 were unclear and could not be determined. This was generally due to a significant degree of magnetopause motion obscuring potential

**Table 5.1:** Key statistics of magnetopause crossings in the case study event.

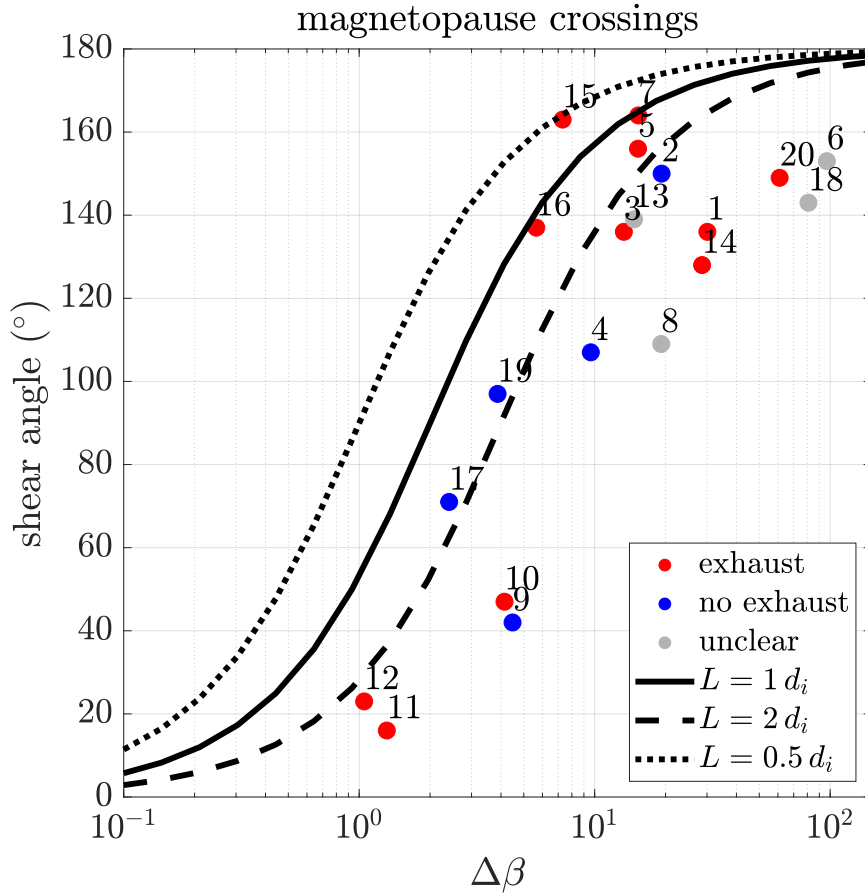
| MP crossing # | probe | $R_X$ | $\Delta\beta$ | shear ( $^\circ$ ) | exhaust | $\Delta V/V_{\text{AL,asym}}$ (%) | agreement |
|---------------|-------|-------|---------------|--------------------|---------|-----------------------------------|-----------|
| 1             | THD   | 0.16  | 30.10         | 136                | Y       | 58                                | N         |
| 2             | THD   | 0.39  | 19.24         | 150                | N       | -                                 | Y         |
| 3             | THD   | 0.37  | 13.30         | 136                | Y       | 59                                | N         |
| 4             | THD   | 0.28  | 9.63          | 107                | N       | -                                 | Y         |
| 5             | THD   | 0.63  | 15.28         | 156                | Y       | 84                                | N         |
| 6             | THE   | 0.09  | 96.84         | 153                | U       | -                                 | -         |
| 7             | THE   | 0.93  | 15.32         | 164                | Y       | 55                                | N         |
| 8             | THE   | 0.15  | 19.17         | 109                | U       | -                                 | -         |
| 9             | THE   | 0.17  | 4.48          | 42                 | N       | -                                 | Y         |
| 10            | THE   | 0.21  | 4.14          | 47                 | Y       | 150                               | N         |
| 11            | THE   | 0.21  | 1.31          | 16                 | Y       | 42                                | N         |
| 12            | THE   | 0.39  | 1.05          | 23                 | Y       | 43                                | N         |
| 13            | THE   | 0.37  | 14.70         | 139                | U       | -                                 | -         |
| 14            | THE   | 0.14  | 28.59         | 128                | Y       | 86                                | N         |
| 15            | THA   | 1.82  | 7.31          | 163                | Y       | 82                                | Y         |
| 16            | THA   | 0.89  | 5.65          | 137                | Y       | 58                                | N         |
| 17            | THA   | 0.59  | 2.41          | 71                 | N       | -                                 | Y         |
| 18            | THA   | 0.07  | 80.89         | 143                | U       | -                                 | -         |
| 19            | THA   | 0.58  | 3.97          | 97                 | N       | -                                 | Y         |
| 20            | THA   | 0.12  | 61.01         | 149                | Y       | 54                                | N         |

*Note.* Magnetopause crossing numbers refer to the crossings labelled in Figure 5.4. Column ‘exhaust’ indicates whether a reconnection exhaust was observed. ‘Y’ denotes that reconnection was observed, ‘N’ indicates no reconnection, and ‘U’ stands for unclear. For those with an exhaust, we calculate the exhaust speed relative to background as a proportion of the asymmetric Alfvén speed. The ‘agreement’ indicates whether the reconnection type observed matches the expectation from the value of  $R_X$ .

exhausts. The strong southward magnetosheath flow seen by THE and THA (due to their distance from the equator) increased the degree of uncertainty in isolating an exhaust. Of the 16 crossings for which the reconnection status could be determined, only 6 are predicted by the value of  $R_X$ . That is, only a 38 % agreement with theory. This is illustrated in Figure 5.6 where each of the magnetopause crossings are shown in the magnetic shear- $\Delta\beta$  parameter space. In this plot, data coloured red are those representing reconnecting current sheets, blue shows non-reconnecting crossings, while grey represents those unclear. As before, we show the limits of the  $\beta$ -shear inequality at  $L = 1, 2$ , and  $0.5 d_i$  levels. Taking these as error estimates, we can say that  $38^{+6}_{-6}$  % of clear crossings agree with the expectation. Of reconnecting crossings, all but one (89 %) are in the reconnection suppressed zone, however no non-reconnecting crossings are in the reconnection allowed zone.

Those determined to be reconnecting are primarily in the high-shear region, as would be expected, though several of these were seen with a large  $\beta$ -asymmetry. In addition, three reconnection events were seen with very low shear angles. These three were all seen by THE in quick succession near the end of the interval (crossings 10, 11, and 12). The repeated magnetopause crossings in this region indicate a rapidly oscillating magnetopause, likely in response to the impact of the particularly large jets seen by THE shortly beforehand. The low shear angles here may be indicators of the deformation caused by this impact, perhaps occurring over a time scale short enough that reconnection was not suppressed. It may also be the case that the exhausts seen here originate from an X-line some distance from the magnetopause crossings, and the deformations seen here are localised effects.

The broad disagreement of observation and theory appears somewhat troublesome. It raises questions about the validity of the theory, as well as the suitability of its application in this study. We discuss this further in Section 5.4.



**Figure 5.6:** Each of the case study magnetopause crossings placed in the  $\Delta\beta$ -magnetic shear parameter space. Red points are for crossings where a reconnection exhaust was observed, blue points denote non-reconnecting crossings, while grey points reflect crossings where it was not possible to determine whether a reconnection exhaust was present.

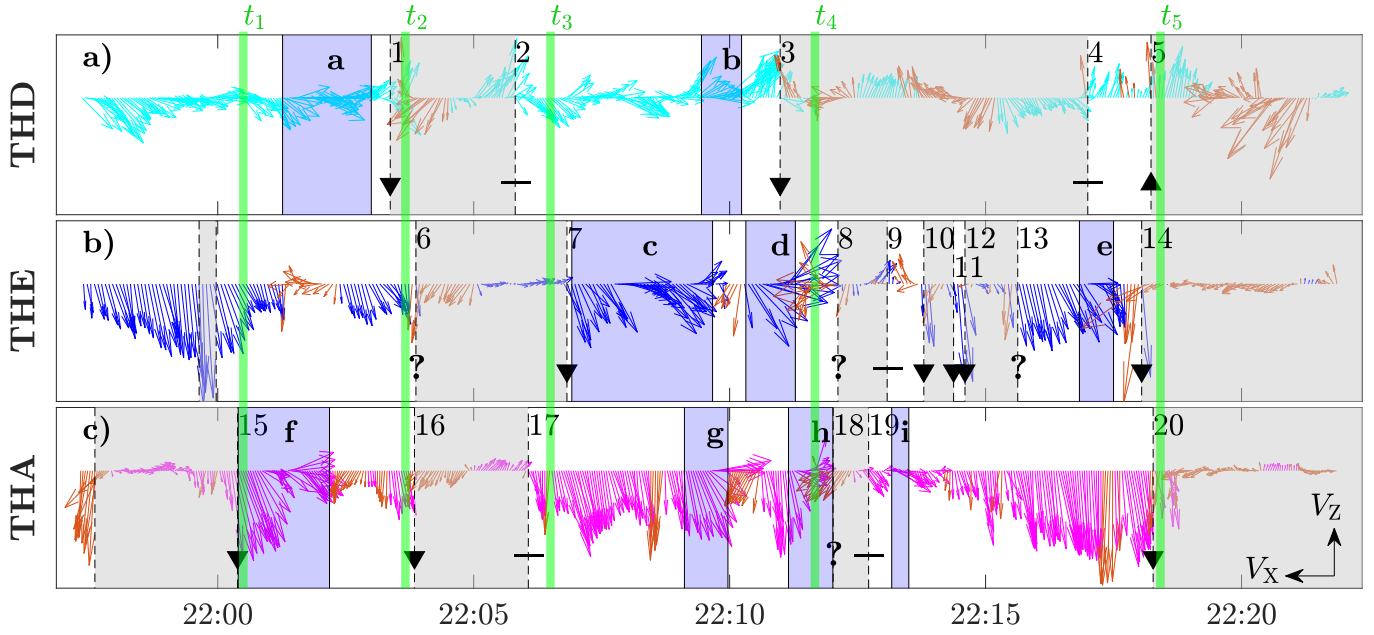


### 5.3.4 Plasma flow and magnetopause motion

The repeated magnetopause crossings in quick succession indicate an extremely dynamic magnetopause, potentially in response to jet impacts. To probe this further, we present Figure 5.7, which is a quiver plot showing the vector directions of the plasma flow measured by each of the THEMIS probes in the X-Z plane. Panels are ordered (as is also the case in Figure 5.4) according to spacecraft latitude, with THD closest to the equator (see orbit plots in Figure 5.3). Note that while the length of the arrows generally corresponds to the magnitude of the velocity, some are automatically shortened in order to minimise overlap and maximise clarity. As with Figure 5.4, blue shaded regions denote jet intervals, while grey regions mark time spent inside the magnetosphere. At each magnetopause crossing a symbol indicates the status of reconnection. Downward pointing triangles represent southward exhausts, while upward pointing triangles denote northward exhausts. Horizontal lines indicate that no reconnection was seen, and question marks show crossings where it was not possible to determine whether an exhaust was present.

In this system, arrows pointed downward indicate southward flow, while arrows pointed to the right represent antisunward flow. As would be expected given the spacecraft locations below the equator, these are the dominant modes. We can clearly see how the spacecraft latitude influences the magnetosheath flow observed. The further the spacecraft from the equator, the greater the dominance and magnitude of the southward flow. THD, being closest to the equator and presumably near the magnetopause stagnation point, sees an almost equal split of northward and southward flow.

In Figure 5.7, we can clearly see that during most jet intervals the arrows are most strongly directed in the negative  $V_X$  direction due to their enhanced antisunward flow. There are, however, instances of sunward (positive  $V_X$ ) flow. These are highlighted in Figure 5.7 by orange arrows directed leftward. We see this most often when inside the magnetosphere or shortly before entering it from the magnetosheath. This can be



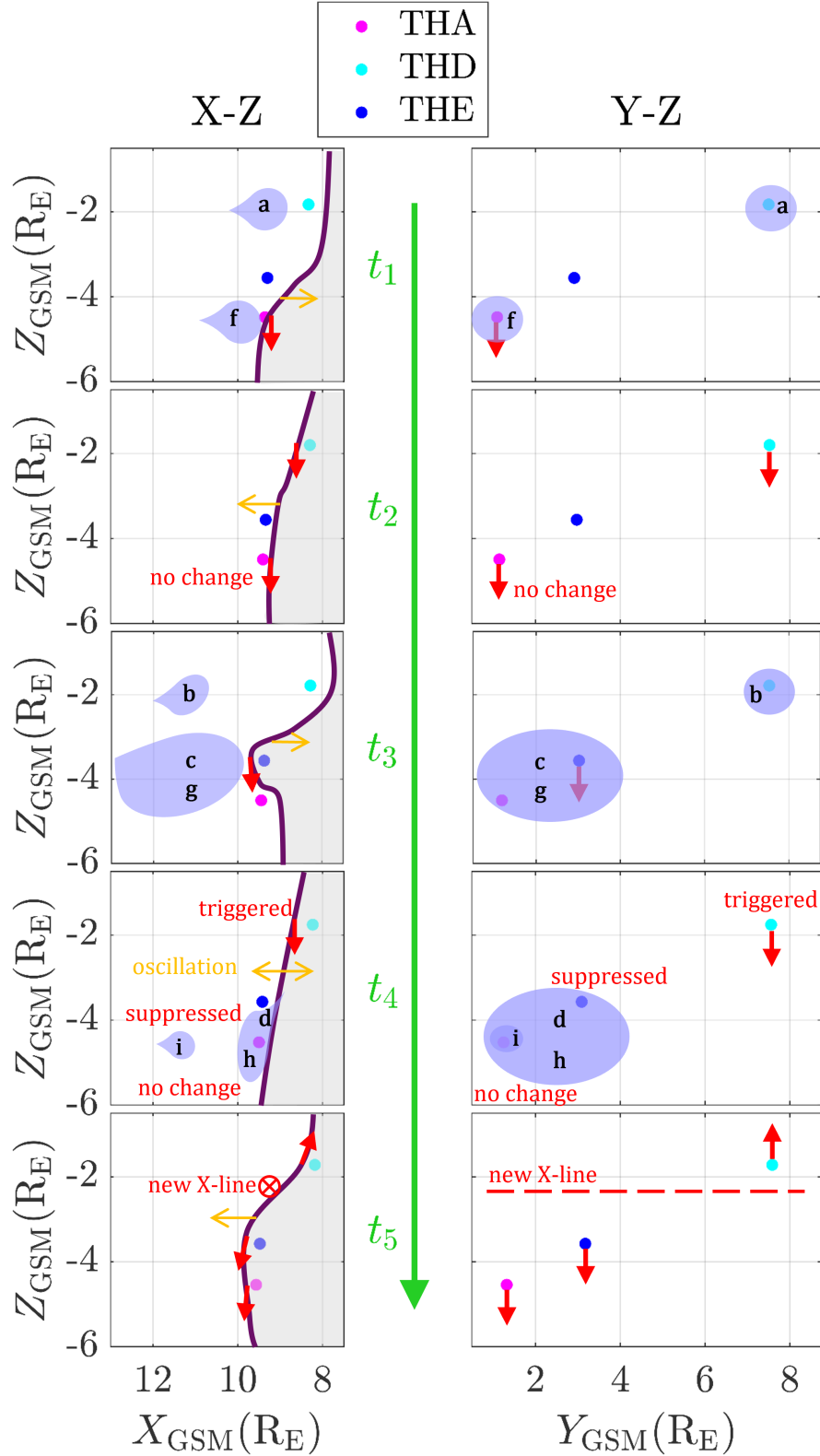
**Figure 5.7:** Quiver plot showing plasma flow velocity direction in the GSM X-Z plane as a function of time. a) THEMIS D observations, b) THEMIS E observations, c) THEMIS A observations. Blue shaded regions denote jet intervals and are labelled a–i in accordance with Figure 5.4, while grey regions show when a spacecraft was inside the magnetosphere with magnetopause crossings numbered. Arrows coloured orange highlight regions with sunward flows, i.e., positive  $V_X$ . Symbols marked at magnetopause crossing indicate the status of reconnection observed there. Downward pointing triangles indicate southward reconnection exhausts, upward pointing triangles indicate northward exhausts, flat lines indicate an absence of reconnection, and question marks indicate an unclear signature. Vertical green lines mark timesteps  $t_1$ – $t_5$  illustrated in Figure 5.8.

interpreted as magnetospheric plasma and magnetopause pile up layer convecting over the spacecraft as it expands outward. In the more extended periods of time inside the magnetosphere, such as that following jet b) seen by THD, we see the magnetospheric plasma oscillating back and forth over the spacecraft, presumably dragged by the magnetopause motion. By considering the points where the flow direction reverses, we can estimate the period of oscillation. Using the magnetospheric time of THD, we see a flow reversal approximately every 80 seconds, which equates to a oscillation frequency of around 6 mHz. This is consistent with observations by previous authors who have seen the magnetopause respond to the impact of transients with frequencies of 2–13 mHz (e.g., Archer and Horbury, 2013; Desai et al., 2021).

## 5.4 Interpretation and discussion

Thus far we have presented the results of a variety of analysis techniques used to probe different aspects of jets and reconnection at the magnetopause in our case study event. In this section we attempt to bring them together to form a holistic picture of the event. We will discuss what we can infer about the possible roles jets may play in reconnection, probe the utility of the  $\Delta\beta$ -shear relation as a predictor of reconnection, and make suggestions for how best to analyse case studies such as these.

Figure 5.8 shows a cartoon illustrating our interpretation of the event and its evolution in time and space by visualising the magnetopause geometry at 5 timesteps ( $t_1$ – $t_5$ ), which correspond to those marked in green in Figure 5.7. At each timestep, we plot THEMIS spacecraft positions in the X-Z and Y-Z planes. Jets are shown in blue and labelled in accordance with Figures 5.4 and 5.7. Their direction of propagation is left to right in the X-Z plane and into the page in the Y-Z plane. By considering the magnetopause crossings seen, we have constructed an estimate of the magnetopause position across the three probes at each time step, enabling us to visualise localised distortions and response to jet impacts. This is marked with a purple line in the figure, with the magnetospheric side shaded in grey. The direction of motion of the magnetopause is shown with orange arrows. This was determined by considering the plasma velocity vectors inside the magnetosphere (as in Figure 5.7), as well as by considering the direction of nearby crossings. Red arrows mark instances when the magnetopause was observed to be reconnecting, their direction indicating whether the exhaust was pointed northward or southward. Note that this is one possible interpretation reached by filling in gaps in both space and time between our in situ observations. We know with a degree of confidence what is happening at particular times and locations (e.g., at a magnetopause crossing), but we can never truly know the behaviour of plasma beyond our field of view.



**Figure 5.8:** Cartoon illustrating a possible interpretation and evolution of the case study event in time and space. Left: X-Z plane; right: Y-Z plane. At each timestep (corresponding to the vertical green lines in Figure 5.7), we depict the estimated position of the magnetopause (purple) and jets (blue) relative to the spacecraft. Observed reconnection exhausts are marked with red arrows, while the direction of magnetopause motion is indicated by orange arrows.

### 5.4.1 The role of jets in reconnection

Reconnection is intermittent throughout the interval. By comparing magnetopause crossings before and after jets, we can attempt to understand their role in reconnection. Our observations are summarised in Table 5.2. When entering the magnetosheath from the magnetosphere, THD did not observe a reconnection exhaust at crossing 2. Around 3.5 minutes later, it encountered jet b). Shortly after, the spacecraft re-entered the magnetosphere at crossing 3, this time observing an exhaust. It is possible, therefore, that the jet played a part in the triggering of reconnection. We are not able to conclusively say, however, that this was the case. In Figure 5.5 we see that, despite some moments with a favourable shear angle, the plasma within jet b) is strongly suppressive due to its consistent high  $\beta$ , averaged at 20 across the interval. It may be the case, however, that the enhanced dynamic pressure exerted on the magnetopause by jet stimulated the onset of reconnection, as was determined to be the case in the event studied by Hietala et al. (2018). This scenario is depicted in timesteps  $t_3$  and  $t_4$  in Figure 5.8.

Magnetopause crossing 7 was determined to be reconnecting. Immediately following this, THE saw jets c) and d) in quick succession (this is the scenario at  $t_3$ ). Shortly after the jets (around  $t_4$ ) followed a series of short magnetopause crossings as the magnetopause rebounded and oscillated, the first of which (8) was unclear, and the second (9) was determined to not be reconnecting. Reconnection resumed shortly after at subsequent crossings (10–12). It is therefore possible that these jets temporarily suppressed the ongoing reconnection at the magnetopause. There is some additional evidence to support this. We can see from Figures 5.5c and 5.5d that the plasma within these jets is mostly in the reconnection-suppressed parameter space, more so than most the jets in the event. This is predominantly due to their particularly high  $\beta$ , with mean values of 60 and 61, which decreases the likelihood of reconnection despite the generally high shear angle. This is also consistent with the result found in Section 4.3.2, that the highest dynamic pressure jets are most likely to be dominated by

**Table 5.2:** Magnetopause reconnection status before and after jet impacts.

| jet | probe | MP before | MP after | % suppressive    | notes                      |
|-----|-------|-----------|----------|------------------|----------------------------|
| a   | THD   | -         | Y        | $63^{+38}_{-25}$ |                            |
| b   | THD   | N         | Y        | $89^{+0}_{-22}$  | Trigger                    |
| c   | THE   | Y         | U/N      | $89^{+3}_{-5}$   | Suppression, same as jet g |
| d   | THE   | Y         | U/N      | $87^{+0}_{-13}$  | Suppression, same as jet h |
| e   | THE   | U/Y       | Y        | $63^{+13}_{-25}$ |                            |
| f   | THA   | Y         | Y        | $62^{+14}_{-19}$ | No change                  |
| g   | THA   | N         | U/N      | $73^{+20}_{-7}$  | No change, same as jet c   |
| h   | THA   | N         | U/N      | $63^{+13}_{-13}$ | No change, same as jet d   |
| i   | THA   | N         | Y        | $50^{+25}_{-10}$ |                            |

*Note.* Jets labels as denoted in Figure 5.4. Magnetopause reconnection status ‘Y’ if seen to be reconnecting, ‘N’ if seen to not be reconnecting, and ‘U’ if unclear. ‘% suppressive’ refers to the proportion of reconnection-suppressive plasma within the jet interval, as shown in Figure 5.5.

reconnection-suppressing plasma.

Reconnection also appears to be intermittent at THA. Distinguishing an exhaust at this spacecraft presented the most difficulty due to the strong southward magnetosheath flow at the spacecraft latitude. At the beginning of the interval, reconnection appears to be occurring at crossing 15, which is seen immediately before jet f), at time  $t_1$ . The closeness of these may mean that the jet was already impacting the magnetopause when the spacecraft entered the magnetosheath and perhaps was responsible for pushing the boundary Earthward over the spacecraft. When the magnetopause rebounded at crossing 16 several minutes later ( $t_2$ ), reconnection appeared to still be occurring. We note the similarity in velocity profile between these two crossings, perhaps indicating sustained reconnection throughout. Later ( $t_3$ – $t_4$ ), jets g) and h) are seen between magnetopause crossings where no exhaust was seen, or could not be determined, once again indicating that the jets produced no change on reconnection.

This interval therefore demonstrates a very interesting situation where each spacecraft

observes a different scenario regarding jets and their role in reconnection: Possible triggering seen by THD, suppression at THE, and sustained/unchanged reconnection at THA. While further analysis and evidence would be required to confirm these results with more certainty, this serves as a demonstration of the complex and variable role jets can play in bursty reconnection, producing effects varying in both time and space.

Looking at the reconnection indicator symbols in Figure 5.7, we can see the variability across the event. The dominant mode for the magnetopause in this time period is reconnecting with southward directed exhausts. This makes sense given the (weakly) southward IMF and spacecraft positions. However, in crossing 5 we observe a clear reconnection exhaust directed northwards (note, this is the example crossing shown in the analysis plot Figure 5.2). This exhaust, seen by THD, comes after a period of southward exhausts, though at the preceding crossing (just over a minute earlier), no reconnection exhaust was seen. Considering the geometry of the spacecraft (Figure 5.3), this would perhaps suggest that the final exhaust seen by THD is from a newly formed X-line at a different, more southern, latitude to that responsible for the exhausts seen earlier in the interval, or that the original X-line has moved. At this moment ( $t_5$ ), all three spacecraft see near-simultaneous magnetopause crossings, perhaps indicating a large boundary motion. This is in contrast to earlier in the interval, where there is a lack of cohesion between the three probes. This demonstrates the locality of the jet impacts on the magnetopause, creating indentations and deformations on scales less than a few Earth radii, as depicted in Figure 5.8. The reconnection exhausts seen by THE and THA are directed southward. It is possible, therefore, that all three probes are seeing outflows from the same new X-line, with THE and THA below it, and THD above.

### 5.4.2 Multi-spacecraft jet observations

Thus far we have treated each of the nine jets observed separately. It is possible, however, that multiple spacecraft are observing the same jets. Using the multi-spacecraft

configuration (Figure 5.3), we can infer some possible scenarios. The average separation between THA and THE throughout the interval was  $2.1 R_E$ , while THD was somewhat further off at  $5.0 R_E$  from THE and  $7.0 R_E$  from THA. Due to this distance (and assuming X-directed propagation), it is very unlikely that the jets seen at THD were also seen elsewhere. However, considering typical jet scales (see, e.g., Plaschke et al., 2020c) it is possible that THA and THE may have observed the same jets. With a mean separation in GSE-X of less than  $0.1 R_E$  (with THA marginally in front), the propagation time of plasma structures from THA to THE would be only a few seconds, making their observation effectively simultaneous provided the structures are large enough in transverse extent.

Jets c) and d) are by far the largest in terms of dynamic pressure enhancement and duration (i.e., parallel size). It may therefore be reasonable to assume that they are also the largest in transverse extent. We see an overlap in time with observations at THA for jets g) and h). Previous estimates of typical jet sizes have exhibited a large degree of variation (see Section 1.4.1), but have been estimated to have an upper limit of  $6 R_E$  in the direction perpendicular to propagation (Hietala et al., 2012). Jets of perpendicular diameter  $2 R_E$  or greater have been estimated to impact the magnetopause 2.4 times per hour under low IMF cone angle conditions (Plaschke et al., 2020c). It is plausible, therefore, that a jet of perpendicular diameter  $2 R_E$  or greater could have been seen by both spacecraft simultaneously. The dynamic pressure enhancements seen at THA are significantly smaller and the jets much shorter in duration than at THE, suggesting that perhaps THA caught outer edges of the structures. If we were to assume that THE saw the middle of the structure where the dynamic pressure peaks, this could suggest a diameter of up to or greater than  $4 R_E$  for these exceptionally strong jets. We also see similarities between the  $\beta$ -shear properties of jets c) and g), as well as between jets d) and h). We therefore infer that these pairs of observations are in fact simultaneous multi-point observations of the same two jets. We illustrate this in Figure 5.8 where the jets are depicted sufficiently large to strike both spacecraft in timesteps  $t_3$  and  $t_4$ . Taking an average velocity across the jet interval and multiplying by the duration, we



estimate their parallel lengths to be  $4.2$  and  $2.4 R_E$ , respectively. Jets f) and i) seen by THA, and e) seen by THE, have no temporal overlap with other jet observations, likely making them smaller in transverse extent than the spacecraft separation of  $2 R_E$ . This is consistent with previous studies that predict jets are most likely at scales well below this (Plaschke et al., 2020c).

### 5.4.3 $\Delta\beta$ -shear of magnetopause crossings

One of the more peculiar results of this investigation is that shown in Figure 5.6, where we compare the  $\Delta\beta$ -shear properties of the magnetopause crossings with the reconnection signatures seen. From our analysis, it would appear that the  $\Delta\beta$ -shear relation, which has been extensively tested (see Section 1.3.2), is not a good predictor of reconnection at magnetopause crossings in this event. Indeed, only 38 % of crossings that could be characterised exhibited an agreement with theory. There are several possible conclusions that could be drawn from this, such as that the theory is redundant, or that our analysis is flawed. We would make the case that neither of these conclusions would be correct. Instead, we think this study provides an opportunity to demonstrate the nuances and caveats that should be considered when conducting magnetopause investigations. It is worth noting that the  $\Delta\beta$ -shear condition is considered to be a necessary but not sufficient condition for the onset of reconnection. That is to say, the magnetopause may be observed with favourable conditions but be prevented from reconnecting due to, e.g., a thick magnetopause layer. This means that, though we do not see any, we would not be concerned if non-reconnecting crossings were fall to the left of Figure 5.6.

Comparing with previous studies that have demonstrated the validity of the  $\Delta\beta$ -shear relation at the magnetopause (chiefly Phan et al., 2013), we note some key differences that may explain discrepancies in our findings. In their study, events with a magnetic shear of less than  $45^\circ$  were excluded from the analysis. This is as the  $\Delta\beta$ -shear relation is formulated for inflow conditions at the X-line. The greater the distance from X-line an

exhaust crossing is made, the less representative the crossing conditions are expected to be of the conditions at the X-line. Considering global X-line models (Trattner et al., 2012), a low shear is generally indicative of a high-latitude X-line, far from the magnetosheath region surveyed. In our study we have several crossings with shear angles less than  $45^\circ$ , but we do not exclude them as these low shears may be due to localised deformations resulting from jet impacts, rather than global curvature. In addition, due to the localised variability jets bring to the magnetopause surface, we would expect that it is often the case that the plasma conditions seen at an exhaust are not representative of those at the X-line in our study. They also require ‘stable’ magnetosheath conditions, which is by design not the case in our event. All this means that our study is of the kind that would have been excluded in previous statistical examinations, due to its complexity.

An additional complication can be seen by noting in Figure 5.4 the occasional presence of cold plasma in the magnetosphere. This is visible as medium density, low energy bands in the ion spectrogram, such as during the period between magnetopause crossings 3 and 4. This is possibly a result of the plasmaspheric plume — a population of cold, dense plasma in the inner magnetosphere (the plasmasphere) that can extend to the dayside magnetopause during times of geomagnetic storms in a drainage plume (e.g., Walsh et al., 2014a). A statistical study by Walsh et al. (2013) found that this is most commonly observed in the dusk sector, detecting a plume in 26 % of magnetopause crossings there. They found observation probability to peak at a magnetic local time (MLT) of 13.6 h. The MLTs of THEMIS probes during this interval are 12.5 h for THA, 13.3 h for THE, and 16.5 h for THD, meaning our case study takes place in the region most likely to encounter the plume at the magnetopause.

The presence of a plasmaspheric plume has been observed to significantly modify reconnection at the magnetopause and present problems for spacecraft observations. The Electrostatic Analyser (ESA) instrument on the THEMIS spacecraft does not have a low enough energy threshold to detect this population ( $< 5$  eV), making it often go

unnoticed except during times of strong magnetopause motion (Walsh et al., 2013). This means that magnetospheric densities may be significantly underestimated. In order to circumvent this, or to study the plasmaspheric plume itself, density can sometimes be estimated via the spacecraft potential as measured by the Electric Field Instrument (EFI). This process is beyond the scope of this present study.

The presence of the plume also lowers the asymmetric Alfvén speed and therefore expected reconnection exhaust speed. If the cold plasma is not taken into account (as is the case in our study), this would then result in reconnection exhausts slower than would typically be predicted. This perhaps explains the exhaust speeds shown in Table 5.1 being a smaller fraction of  $V_{A,asym}$  than would usually be expected in reconnection. The plume is also understood to lower outflow speeds by mass loading (Walsh et al., 2014b), which would make them more difficult to distinguish from background flow, particularly at higher latitudes. It has also been noted by Phan et al. (1996) that when the magnetosheath exhibits particularly high  $\beta$  (as is the case with jets at the magnetopause), the agreement of observed exhaust speed with that predicted by the Walén relation is weakened.

The exact effect of the cold plasma population on the magnetospheric  $\beta$  is not clear, as it presents both an increase in density and a decrease in temperature. It does, however, introduce a significant uncertainty to our calculation of  $\Delta\beta$ . If the true  $\Delta\beta$  were to be smaller than the measured value, this would shift the points in Figure 5.6 to the left, towards the reconnection-favourable zone. This may explain the number of crossings that were observed to be reconnecting but fell in the reconnection-suppressed zone of the parameter space. We notice that many of the reconnecting crossings, though below the curves in Figure 5.6, do follow the general shape of the boundary. That is to say, we only observe low-shear reconnection at relatively low  $\Delta\beta$ , so that if the boundary were shifted by lowering the  $\Delta\beta$  these points would likely obey the relation. In the statistical study of Phan et al. (2013), events displaying evidence of cold plasma required additional information (in the form of distribution functions) in order to

confirm reconnection. This was not within the scope of our study, though it would be required for further analysis on this or similar events.

This serves as a useful demonstration of the complexities of magnetopause reconnection case studies, and the care that should be taken when applying the  $\Delta\beta$ -shear condition. We note that events such as this, with unsteady and locally varying inflow conditions, significant magnetopause motion and deformation, and evidence of cold plasma, are often explicitly excluded or require additional information in statistical studies (e.g., Phan et al., 2013) due to the difficulty in automating the analysis techniques.

These findings may appear to call into question the methodology and results of Chapter 4, where we made extensive use of the  $\beta$ -shear relation as a predictor of how jets may affect reconnection at the magnetopause. It does not, however, invalidate the investigations and results presented there. There are several reasons for this. Firstly, this only one case study event. As such, we would be hesitant to base all our understanding of diamagnetic suppression of reconnection on our findings here, especially given the significant body of previous work that exists to validate the theory. Secondly, the methods of Chapter 4 used only magnetosheath observations, neglecting magnetospheric  $\beta$  and assuming a perfectly northward field at the magnetopause. We see now that these assumptions may not always hold true, particularly as jets disturb and indent the field at the magnetopause following impact. However, in the absence of direct magnetopause observations, it seems a reasonable best approximation of the magnetopause conditions, as we cannot know the state of the magnetopause at that moment or what conditions it may have been subject to previously. The results of this case study highlight that we should proceed with care when using the  $\Delta\beta$ -shear condition on a case-by-case basis, but when applied in a statistical sense it is useful for telling us how we would expect jet plasma to interact with an average magnetopause.

## 5.5 Conclusions and future work

In this study we aimed to shed light on how the magnetopause responds to jet impacts, particularly in terms of magnetic reconnection. By way of a case study we developed analysis techniques that can be applied to events such as these. We have seen that jets are intrinsically linked to bursty reconnection at the magnetopause during a period of quasi-radial IMF, with this 25 minute event potentially demonstrating jets both triggering and suppressing reconnection. We see that jets can significantly disturb the magnetopause, creating oscillations and deformations on scales below a few  $R_E$ , with larger jets having greater influence. We have seen that the  $\beta$ -shear characteristics of jets can help inform their reconnection capabilities, but that this theory cannot always be confidently applied at the magnetopause.

While we have uncovered a lot of detail about this case study event, there are several other avenues of investigation that can be taken, which we suggest for future work. The focus of this study, in accordance with the work presented previously in this thesis, is on the link between jets and localised reconnection at the magnetopause. We have not, therefore, conducted in-depth analysis on magnetopause motion and deformation following jet impacts. This has been the subject of study by numerous previous authors such as Archer et al. (2019), Amata et al. (2011), and Escoubet et al. (2020). To better understand the event geometry, one can study the magnetopause normal vectors (as determined from MVA), the difference between them and the quiet-time magnetopause normal for the same solar wind conditions, and their variation in space and time. This will likely illustrate the localised deformation resulting from jets impacting the magnetopause. Similarly, we can conduct further analysis into the potential wave-properties magnetopause oscillation seen.

For a given reconnection exhaust observation, one can make a crude estimate of the distance from X-line. The reconnection rate is assumed to be 0.1 and the exhaust opening angle  $11^\circ$  (Cassak et al., 2017), and therefore by estimating the exhaust width based on spacecraft crossing duration and ambient  $V_N$ , the distance from X-line can be calculated

from simple geometry (e.g., Øieroset et al., 2016; Eastwood et al., 2018). However, this is best performed for reconnection exhausts in the solar wind, where they can often propagate to extremely large distances unimpeded (e.g., Phan et al., 2006). More sophisticated methods to estimate the X-line distance include using a magnetospheric field model (e.g., Tsyganenko, 1995) and considering different ion populations observed in reconnection boundary layers (e.g., Fuselier et al., 2019). This is beyond the scope of this study, however, one could attempt this in order to more confidently reconstruct the X-line geometry of the case study event and compare to global models such as the maximum magnetic shear model (Trattner et al., 2012).

Another important consideration when studying reconnection at the magnetopause is the thickness of the magnetopause layer. This was demonstrated by Hietala et al. (2018) in their case study of a jet triggering reconnection. By considering electron pitch angle distributions, electric field measurements, and multi-spacecraft timing analysis, they inferred that the high dynamic pressure of the jet resulted in a compression of the magnetopause current sheet such that it was able to initiate the onset of reconnection. This is not something that has been explicitly considered in our study, however a systematic application of this would likely shed light on factors influencing reconnection beyond the beta-asymmetry and magnetic shear.

As well as these possible developments to the present case study, we suggest that similar studies be performed for intervals with different IMF conditions, e.g., strongly northward  $B_z$ . Considering the nuances and potential pitfalls highlighted here, we hope that it may be possible to build towards a statistical data set of jet impacts at the magnetopause to better understand their typical role in reconnection. This may be possible using combinations of multi-spacecraft missions such as the upcoming Helioswarm, which will provide excellent coverage of Earthward magnetosheath flow, making for many opportunities to observe jets, while small-separation missions such as MMS can provide simultaneous coverage of the magnetopause, observing reconnection signatures in unprecedented detail. It is believed that both MMS and THEMIS will

soon enter string-of-pearl formations, also making it possible to track the temporal and spatial development of a jet impacting the magnetopause and its response.

## Chapter 6

# Conclusion

Magnetosheath jets are planet-sized impulsive plasma transients formed at Earth's bow shock. As flows of mass and energy, they couple the solar wind and foreshock to the magnetopause and inner magnetosphere, and are a unique and exciting laboratory for studying some of the most fundamental plasma physics.

In their comprehensive review of magnetosheath jets from early evidence to large statistical studies, Plaschke et al. (2018) posed many open and unsolved questions. These were spurred by community discussions and the work of ISSI team 350 (<https://www.issibern.ch/teams/collisionlessshocks/>). The questions were wide-ranging, and included points on jet occurrence, properties, their relation to the upstream solar wind, and their role in magnetopause reconnection. In this thesis we have attempted to answer some of these questions using a database of 13,096 jets identified by the THEMIS spacecraft, accompanied by upstream solar wind conditions from the OMNI database, spanning 11 years. Our analysis has mainly been statistical, utilising the wealth of data available to us in the largest statistical study of its kind at the time.

In Chapter 3 we addressed the need to make connections between upstream solar wind conditions and a jet's ability to penetrate the magnetosheath and impact the magnetopause, with a view to building forecasting capabilities, which was specifically



highlighted by Plaschke et al. (2018) as an unsolved problem. The work presented represents a significant advancement in this area in that now we have statistical evidence for the conditions that produce the highest numbers of jets impacting the magnetopause.

We investigated the factors affecting jet formation, and found that a number of parameters had a notable influence, including some trends that previous studies with smaller data sets were not able to distinguish. Due to the size of our data set, we were able to restrict our analysis to only jets observed at the bow shock, which previous studies had not been able to do confidently. In doing so, and by comparing the results with those seen at the magnetopause, we arrived at the somewhat surprising result that the solar wind factors affecting jet formation are not the same as those that encourage jet propagation to the magnetopause. Combining both formation and propagation effects, we established the solar wind conditions for which jets are most likely to impact the magnetopause at the highest rates. We found these conditions to be low IMF cone angle, high solar wind speed, and, to a lesser extent, low density. We noted that these are conditions typically associated with fast type solar wind. This is a significant step towards being able to forecast and model the magnetospheric impacts of jets.

Following the publication of LaMoury et al. (2021), these results have been useful for the community, laying the groundwork for further investigation into the specific drivers and ramifications of solar wind modulation of jet formation and impacts. This was done by Koller et al. (2022) in the context of large-scale solar wind transients. Studies concerning the interdependence of the solar wind parameters, and the possible variation of jet occurrence across the solar cycle, are also currently in development. Our significant result that solar wind conditions affect the formation and propagation of jets differently has also spurred a change in methodology for the community in that studies on jet origins must now restrict their scope to jets observed near the bow shock only, in order to disentangle formation and propagation effects.

Having established when jets are most likely to impact the magnetopause, it is natural to turn attention to the properties and possible effects of jets once there. In Chapter 4

we did just that, focusing on the properties of jets in the magnetosheath most relevant to magnetic reconnection. In their review, Plaschke et al. (2018) also highlighted the need to study the variation of jet properties within the magnetosheath. We did this by comparing the distributions of properties for jets observed near the bow shock with those observed near the magnetosheath, and also with the non-jet magnetosheath. We established that jets near the magnetopause typically retain their thermal properties throughout propagation, though the disparity with the background magnetosheath widens. We saw that jets at the magnetopause typically have a higher  $\beta$  than the magnetosheath at large. Considering the  $\beta$ -shear relation for reconnection, this would suggest that jets may suppress reconnection at the magnetopause, which is at odds with the study of Vuorinen et al. (2021) that found that jets could trigger reconnection during northward IMF by virtue of their  $B_z$ .

We explored this conflict by placing observations in the  $\beta$ -shear parameter space, first using the non-jet magnetosheath to establish how often the condition is fulfilled under varying IMF orientations, and then using jet plasma at the magnetopause. To the best of our knowledge, this is the first time that the magnetosheath has been parameterised in this manner and to this extent. We found that, primarily due to the enhanced  $\beta$ , jet plasma is more likely to suppress reconnection than the non-jet magnetosheath under all IMF orientations. We also found, however, that each jet interval is sufficiently variable in its magnetic field that most jets contain at least one moment where the conditions are such that reconnection may be modified from the IMF-based prediction. We also established that the highest dynamic pressure jets are most likely to contain reconnection-suppressing plasma. These results break with the tradition of studies involving jets and reconnection and represent a paradigm shift, in that previous literature has focused on the potential of jets triggering reconnection without investigating their possible role in reconnection suppression. Our results made it clear that the role of jets in magnetopause reconnection is complex and varied.

There are many possible avenues of extension for this investigation. Considering

the properties of jets in the magnetosheath and their variation from bow shock to the magnetopause, one can further explore what this signifies about the type of jets that are most likely to reach the magnetopause, making connection to the upstream solar wind conditions and formation mechanisms. This would add to the predictive capabilities of forecasting models, allowing us to not only infer how many jets will impact the magnetopause for a given solar wind condition, but also what their properties are likely to be. In terms of reconnection it would be interesting to study the  $\beta$ -shear conditions of periods before, after, and between jets to ascertain how they affect their surroundings at the magnetopause, with a view to understanding the reinforcement or relaxation time required to produce prolonged modifications to magnetopause current sheets.

While predictive statistics are extremely powerful, they carry more weight when supplemented with case examples. The aim of Chapter 5 was to select and explore a case study event to illustrate our previous results, and to develop and test analysis tools for studying the magnetopause response to jet impacts. By filtering the jet database according to their likelihood to modify reconnection from the IMF-expectation, we selected an event where three THEMIS probes, separated by a few  $R_E$ , made 9 jet observations and 20 magnetopause crossings in a 25-minute window, indicating an extremely active, dynamic, and rich event. To analyse each magnetopause crossing, we performed minimum variance analysis and characterised possible reconnection exhausts, comparing with the asymmetric Alfvén speed. We estimated the  $\beta$ -shear parameters for magnetosheath plasma, and calculated  $\Delta\beta$  and the magnetic shear directly at each crossing in order to compare our reconnection observations with the theoretical prediction.

We found reconnection to be intermittent throughout the interval, turning on and off in a bursty fashion. We saw possible evidence for jets both triggering and suppressing local reconnection at the magnetopause within the same interval, reinforcing the results we saw in the previous chapter, that both situations are possible. We saw that the  $\Delta\beta$  condition was not a good predictor of whether a given magnetopause crossing would be

reconnecting, showing agreement only 38% of the time. We explained this by noting the evidence cold magnetospheric plasma, possibly as a result of the plasmaspheric drainage plume, which may have the effect of altering the magnetospheric  $\beta$  in a way that we are unable to measure and account for in our calculations. We therefore regard this as a demonstration of the care that must be taken when applying this theory to magnetopause studies. Note that we do not consider this to invalidate our investigations in Chapter 4, which centred on using the  $\beta$ -shear condition as a predictor for reconnection favourability, as the reasons for its poor performance in Chapter 5 chiefly arise from the magnetospheric conditions and difficulty in determining exhaust parameters. Our estimates in Chapter 4 were made using magnetosheath plasma only, predicting whether jets have the ability to modify reconnection via these parameters, but not predicting how the magnetopause would respond.

By visualising plasma velocity vectors we saw that the magnetopause oscillated and rebounded in response to jet impacts, with deformations produced on localised scales and therefore were not consistently seen across all spacecraft. By considering the strongest jets that were possibly observed by multiple spacecraft, we were able to estimate or infer details about their size, the largest being at least  $2 R_E$ , and potentially beyond  $4 R_E$ , in both parallel and perpendicular extent, though most were believed to be below  $2 R_E$  in transverse size. Though not a conclusive or exhaustive investigation, through our case study we demonstrated how magnetopause reconnection in response to jets can be studied, and evidenced their disruptive yet localised effects. Future studies can apply these techniques to a variety of events under varying solar wind conditions to build a more complete picture of how jets typically affect reconnection at the magnetopause.

Since commencing this research project, a golden age of magnetosheath jet research has dawned. There is a greater interest in jets, driven by a greater number of researchers, than ever before. Our understanding is rapidly advancing, yet there is still much to learn about this fickle but fascinating phenomenon. The search for jets at other shock

environments is still in its infancy, though very recent results from Gunell et al. (2023) show promising evidence for jets in the martian system. With the ever-increasing wealth of inner-heliosphere data thanks to the Parker Solar Probe (Fox et al., 2016) and Solar Orbiter (Müller et al., 2020) missions, we expect that observations of jets at interplanetary shocks may soon be detailed. The link between jets and the quasi-parallel shock is now extremely well established. However it has become clear that jets can also be observed in the quasi-perpendicular magnetosheath, as well as the boundary region between the two. In addition, it seems that there is mounting evidence for a variety of jet generation mechanisms beyond that associated with bow shock ripples. It is therefore likely that future investigations will further distinguish between these different types of jets, making links between their properties and origins, such that they can be treated as separate phenomena.

The analogy made by Vuorinen et al. (2022a) (to which this author contributed) illustrates the role of jets in the wider space weather context. If the conventional weather equivalents of CMEs and flares are hugely disruptive and extreme events such as hurricanes and tornadoes, then jets are more like rain. That is to say, in isolation, individual droplets are unlikely to be damaging, but the cumulative effects of many can be more serious. Discrete in form but near-continuous in impact, the forecasting of individual jets is neither possible nor productive. Instead we ought to be concerned with when they are likely to occur and impact the magnetopause at the highest rates. We have made substantial steps towards linking the upstream solar wind to magnetopause processes via jets. The next step in the pipeline is to assess the space weather ramifications of jets impacting the magnetopause. Some progress has already been made regarding auroral signatures and substorm onset, but further investigation must be conducted to link these and other processes, such as radiation belt excitement, to the upstream solar wind with a view to eventual forecasting.

One of the reasons that jets are not currently considered from a space weather perspective is the difficulty in simulating them in real time. The global models used for this are

typically based on MHD, therefore without capabilities to establish a foreshock. Jets are mesoscale structures, but their formation and interaction with their surroundings is fundamentally kinetic, making it unlikely that we will be able to fully incorporate them into these models. Instead, perhaps we should turn to probabilistic statistical models where large observational data sets can be used to predict the likely space weather effects arising from jets for a given solar wind input. The results presented in this thesis may prove vital in the development of this tool. Though measurements of the solar wind at L1 may generally be useful in predicting the global response, we must also account for the internally-generated processes that can drastically alter the conditions at the magnetopause from our expectation.

With such high occurrence rates, particularly downstream of the quasi-parallel shock, jets should be viewed as a fundamental and intrinsic part of the magnetosheath and the solar-terrestrial link at large. We often make comparisons between the properties of jets and ‘normal’ magnetosheath plasma, but it is arguable that the normal state of the magnetosheath is for it to contain jets. In this thesis we have illustrated their importance and helped to uncover the processes behind the formation, propagation, and resulting effects of magnetosheath jets from the bow shock to the magnetopause.

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