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ISBN

9798247923831

Author

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Publication Date

2026-05-27

Peer reviewed|Thesis/dissertation

UNIVERSITY OF CALIFORNIA

Los Angeles

Kinetic-scale Solar Wind Current Sheets: Statistical Characteristics and Their Role in
Energetic Particle Transport

A dissertation submitted in partial satisfaction of the
requirements for the degree Doctor of Philosophy
in Planetary Science

by

Zijin Zhang

2026

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Zijin Zhang

2026

ABSTRACT OF THE DISSERTATION

Kinetic-scale Solar Wind Current Sheets: Statistical Characteristics and Their Role in Energetic Particle Transport

by

Zijin Zhang

Doctor of Philosophy in Planetary Science

University of California, Los Angeles, 2026

Professor Vassilis Angelopoulos, Chair

The transport of solar energetic particles (SEPs) through the heliosphere is governed by their interaction with the highly variable interplanetary magnetic field. Yet standard quasi-linear models, which assume scattering by small-amplitude, randomly phased fluctuations, fail to account for current sheets, coherent, intermittent structures that pervade the solar wind. This dissertation develops a quantitative, observation-informed framework for understanding how kinetic-scale current sheets scatter energetic particles and shape their transport across the inner heliosphere. On the observational side, we analyze more than 175,000 current sheets identified by Parker Solar Probe (0.17 AU), Juno (1–5 AU), ARTEMIS, WIND, and STEREO using a robust, time-resolution-independent detection algorithm. We find that their normalized thicknesses (2–4 ion inertial lengths) and current densities (0.05–0.15 Alfvén current densities) remain broadly invariant across 0.17–5 AU and follow an inverse current density–scale relation spanning several orders of magnitude. Theoretically, we develop an exact Hamiltonian description of particle motion in force-free current sheets and conduct extensive test-particle simulations parameterized by the observed property distributions at 0.1 and 1 AU. We find that the scattering is dominated by geometrical chaotization, the destruction of the quasi-adiabatic invariant at separatrix

crossings, which produces order-unity pitch-angle jumps within single interactions, a mechanism qualitatively distinct from resonant wave-particle diffusion. By evaluating the aggregate effect of multiple, sequential interactions through a Monte Carlo transport model, we show that both parallel and perpendicular diffusion coefficients exhibit asymptotically diffusive behavior, but with a perpendicular-to-parallel ratio that increases with particle energy and exceeds standard quasi-linear predictions above 1 MeV. These results identify current sheets as efficient drivers of energetic particle scattering throughout the inner heliosphere, offering a natural explanation for SEP transport phenomena that have long challenged purely wave-based models, including broad particle reservoirs and rapid longitudinal spreading.

The dissertation of Zijin Zhang is approved.

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2026

To my mother,
whose kind heart, quiet courage, and unwavering love
have carried me further than I will ever know.

献给我的母亲
您的善良、坚韧与爱
伴我走过此生最远的路。

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Acknowledgments

I owe my deepest gratitude to my advisors, Professor Vassilis Angelopoulos and Anton Artemyev, for their guidance, patience, and unwavering support throughout my doctoral studies. They granted me the freedom to pursue my own research interests and encouraged me to explore the broader scientific landscape, while always providing the insight and direction I needed to move forward.

I am also deeply thankful to the members of my doctoral committee, Professors Marco Velli, Hao Cao, and Paulo Alves, for their time, thoughtful feedback, and valuable perspectives that have strengthened this work.

I am profoundly grateful to my parents for their unconditional love and support. They gave me the freedom to explore the world and the confidence to chart my own path. Their spirit of curiosity and perseverance has been a lasting source of inspiration.

I also wish to thank my friends (Xiaofei Shi, Sergei Kamaletdinov, Wenke Zhong, Henry Zhu, Siyu Wu, Hanlin Xiao, Jerry Liu, Sophie Ye, and many others), roommates (Kyle Webster, Travis Gilmore, Saeed Mohanna, Eric Sinski, Hanzhang Chen and Liuwei Xu), and climbing partner (Jinbang Chen) for making these years not only productive but genuinely joyful. Their companionship, humor, and shared adventures have been an essential part of this journey.

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Publications

1. **Zhang, Z.**, Artemyev, A. V., Angelopoulos, V., & Zhang, X.-J. (2026). Peculiarities of Precipitating Electron Spectra Revealed through a Combined DMSP-ELFIN Dataset. *Journal of Geophysical Research: Space Physics*, under review.
2. **Zhang, Z.**, Shi, X., Kamaletdinov, S., Artemyev, A., Angelopoulos, V., & Velli, M. (2026b). Multifluid Equilibrium Model of Current Sheets with Interpenetrating Ion Beams. *Physics of Plasmas*, under review.
3. **Zhang, Z.**, Artemyev, A., Angelopoulos, V., Phan, T., & Shi, C. (2026a). Comparison of Solar Wind Current Sheets in the Inner Heliosphere. *The Astrophysical Journal*, 1000(1), 21. <https://doi.org/10.3847/1538-4357/ae46a1>
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<https://doi.org/10.1029/2024JA033174>

Chapter 1

Introduction

1.1 Overview

The solar wind is a hot, magnetized plasma that continuously expands from the solar corona into interplanetary space, driven by the pressure gradient between the dense coronal plasma and the surrounding interstellar medium (Parker, 1958; 1965a; Velli, 1994; 2001). As it propagates outward, the solar wind accelerates to super-Alfvénic speeds, transporting mass, momentum, and energy throughout the heliosphere. Because the solar wind is highly electrically conductive, magnetic field lines are frozen into the plasma flow to a good approximation. The resulting large-scale interplanetary magnetic field (IMF) is shaped by the combination of radial expansion and solar rotation, producing the Archimedean spiral geometry described by the Parker model—a configuration well supported by observations when averaged over sufficiently long intervals (Zhao et al., 2025a; 2025b).

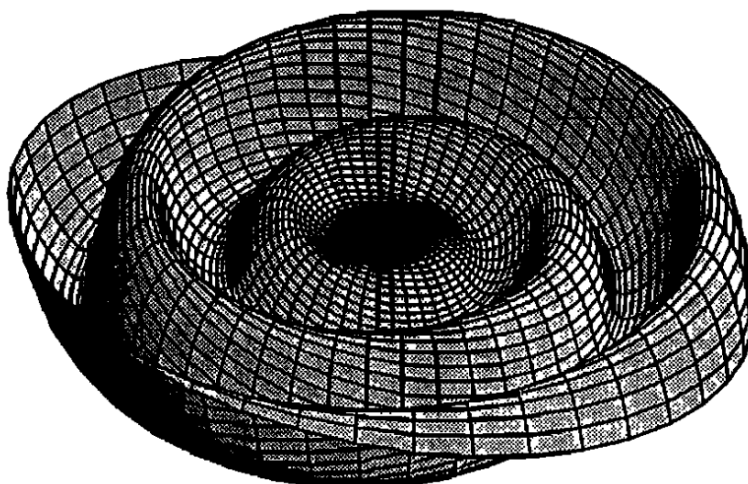


Figure 1.1: Three-dimensional representation of the HCS inside the heliosphere. The tilt of the solar magnetic dipole relative to the rotation axis causes the current sheet to form a warped, spiraling surface that a spacecraft near the ecliptic crosses twice per solar rotation (Jokipii & Thomas, 1981).

The most prominent large-scale structure arising from this magnetic topology is the heliospheric current sheet (HCS)—the thin surface separating open field lines of opposite polarity (Smith, 2001). The dipole tilt and solar rotation warp this surface into a spiraling “ballerina-skirt” geometry (Figure 1.1) that extends throughout the heliosphere. In situ, the HCS manifests as a sharp IMF polarity reversal; Parker Solar Probe observations confirm this structure persists from close to the Sun out to 1 AU, with the large-scale geometry remaining stable while the small-scale plasma structures surrounding the sheet evolve substantially during outward propagation (Figure 1.2) (Szabo et al., 2020).

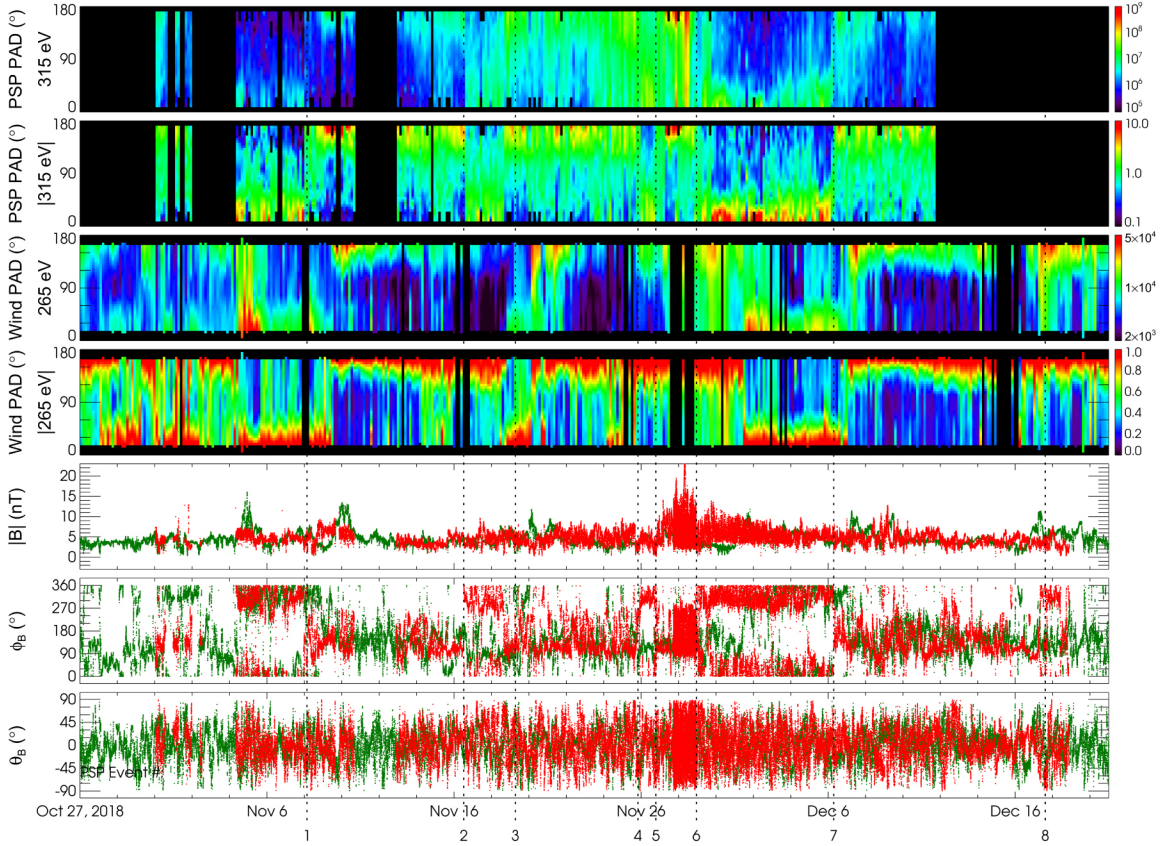


Figure 1.2: Comparison of HCS crossings observed by PSP and Wind with the PSP data forward shifted and magnetic field scaled. The upper two panels are the PSP 315 eV electron PADs (in flux units and normalized) propagated to the location of Wind. The next two panels are the 265 eV Wind electron PADs. The bottom three panels show the Wind observed magnetic field (green) and scaled PSP measurements (red) in spherical coordinates. Vertical dotted lines show the time of the propagated PSP HCS events

Superposed on this ordered background, however, are fluctuations spanning a broad range of scales and magnitudes. These fluctuations are a manifestation of magnetohydrodynamic (MHD) turbulence (Bruno & Carbone, 2013; 2016; Goldstein et al., 1995; Matthaeus, 2021;

Schekochihin, 2022; Tu & Marsch, 1995), which is multi-scale, intermittent, and strongly non-Gaussian (Bruno, 2019; Chandran et al., 2025; Matthaeus et al., 2015; Verscharen et al., 2019). A key feature of this turbulence is that energy does not distribute uniformly across space as it cascades from large to small scales. Instead, it concentrates into localized, coherent structures — magnetic flux ropes, magnetic holes, plasma waves, and current sheets (Khabarova et al., 2021; Perrone et al., 2020; Pezzi et al., 2021) — which actively feed back into the plasma, contributing to heating, particle acceleration, and departures from classical MHD behavior (Borovsky, 2010; De Giorgio et al., 2017; Greco et al., 2017; Li et al., 2011).

Among these coherent structures, current sheets—thin layers of intense electric current where the magnetic field direction changes abruptly—are the most prominent and dynamically significant (see Section 1.3 for a comprehensive review). First identified in Pioneer 6 measurements as sharp directional changes in the interplanetary magnetic field (Colburn & Sonett, 1966; Ness et al., 1966), they were initially classified within the MHD discontinuity framework as tangential discontinuities (separating topologically distinct plasma regions with no normal field component) or rotational discontinuities (propagating Alfvénic structures connecting magnetically linked regions) (Hudson, 1970). The relative abundance of these two discontinuity types and their physical significance for magnetic topology have been subjects of longstanding debate (see Subsection 1.3.1) (Neugebauer, 2006). High-resolution measurements from missions such as ARTEMIS, MMS, and Parker Solar Probe have since revealed that many current sheets possess fundamentally kinetic properties: their thicknesses are on the order of a few ion inertial lengths, and their internal structure—including temperature anisotropy and non-gyrotropic ion distributions—defies a purely MHD description (Artemyev et al., 2019a; Vasko et al., 2022). Statistically, current sheets are ubiquitous throughout the heliosphere, with occurrence rates exceeding 100 events per day at 1 AU (Zhang et al., 2025a) (see Subsection 1.3.3.3). Their normalized properties—thickness in units of the ion inertial length and current density in units of the Alfvén current density—exhibit a pronounced inverse correlation (stronger currents in thinner sheets) that extends over several orders of magnitude (see Subsection 1.3.3.4), suggesting a universal feature of the turbulent cascade (Vasko et al., 2024). The observational characterization of these properties across the inner heliosphere is developed in Chapter 2 and Chapter 3.

The heliosphere thus presents two interleaved levels of magnetic organization: the ordered global structure of the Parker spiral and HCS, and the smaller-scale turbulence and coherent structures embedded within that background. This multiscale magnetic environment strongly influences heliophysics processes, especially the transport of energetic particles. Large-scale topology determines magnetic connectivity while small-scale structures govern local scattering and confinement.

Solar energetic particles (SEPs) are high-energy ions and electrons episodically accelerated in the solar and interplanetary environment (Anastasiadis et al., 2019; Desai & Giacalone, 2016; Klein & Dalla, 2017; Reames, 2013) (see Subsection 1.4.1). They originate either in the low solar corona during eruptive events (impulsive SEP events, associated with magnetic reconnection in solar flares), or at interplanetary shock fronts driven by fast coronal mass ejections (gradual SEP events, driven by diffusive shock acceleration) (Desai & Giacalone, 2016; Reames, 2013). SEP events pose radiation hazards to spacecraft electronics, astronauts, and high-altitude aviation, and they provide a natural laboratory for studying particle acceleration and transport in magnetized plasmas—with implications extending to astrophysical systems more broadly.

Two contrasting observational signatures of SEP transport provide particularly compelling evidence for the role of magnetic structures in controlling particle propagation (see Subsection 1.4.1.3 for a detailed discussion). The reservoir effect—in which widely separated spacecraft observe nearly identical particle intensities and spectral shapes during the decay phase of large gradual events (Dalla et al., 2003; Reames, 2013) —implies substantial cross-field transport that distributes particles throughout a large heliospheric volume. In contrast, dropout events—abrupt depletions of particle intensity at current sheet crossings (Mazur et al., 2000; Tessein et al., 2015) —indicate that particles can be effectively confined within individual magnetic flux tubes, with current sheets acting as barriers at their boundaries. Together, these phenomena reveal a fundamental duality: current sheets can both impede and facilitate particle transport, depending on their internal structure and the particle energy.

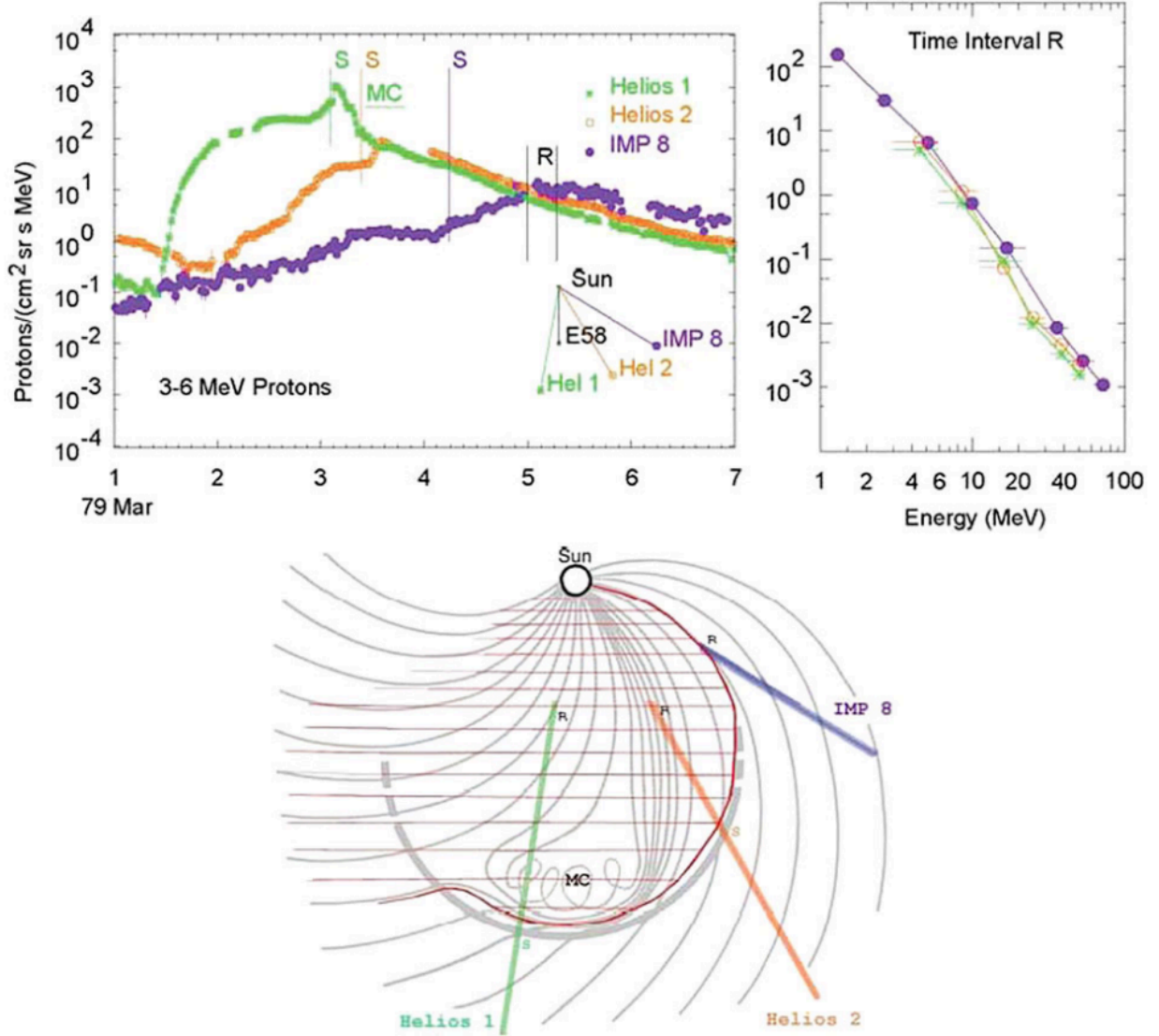


Figure 1.3: The reservoir effect in solar energetic particle events. Left: proton intensities at several energies measured by Wind/LEMT during the 1997 November 6 event, showing uniform decay profiles across energies after the initial rise. Right: energy spectra at successive times remain nearly identical in shape (invariant spectra), indicating that particles have filled a large heliospheric volume and are decaying uniformly. Bottom: schematic of spacecraft positions relative to the Sun. Such spatially uniform distributions imply substantial cross-field transport, potentially mediated by interactions with current sheets and other coherent structures (Reames, 2013).

The standard theoretical framework for SEP propagation is the quasi-linear theory (QLT) of pitch-angle scattering (Jokipii, 1966) (see Subsection 1.4.1.4), which treats the turbulent magnetic field as a superposition of small-amplitude, randomly phased waves and derives diffusion coefficients from the resonant interaction between particles and fluctuations at

the cyclotron frequency. However, growing observational and numerical evidence demonstrates that the fine-scale magnetic structure of the solar wind—in particular, its coherent, intermittent character—can exert a decisive influence on particle dynamics that QLT does not capture (Artemyev et al., 2020a; Malara et al., 2021; 2023).

When a particle’s gyroradius becomes comparable to the thickness of a current sheet, the standard guiding-center approximation fails because the magnetic field varies on scales smaller than the gyro-orbit. In this regime, the magnetic moment μ is no longer the appropriate conserved quantity. Instead, the dynamics are governed by the quasi-adiabatic invariant I_z —the action variable of the fast oscillation normal to the current sheet (Büchner & Zelenyi, 1989; Zelenyi et al., 2013) (see Subsection 1.4.2 for the full theoretical development). This invariant is approximately conserved during regular motion but undergoes jumps at separatrix crossings in phase space, where the particle transitions between qualitatively different types of oscillation (e.g., from gyration on one side of the sheet to figure-eight orbits spanning both sides). In symmetric current sheets without a guide field, these jumps are small and accumulate diffusively. However, in force-free current sheets—where the intermediate magnetic field component peaks at the center, breaking the phase-space symmetry—geometrical chaotization produces order-unity jumps in I_z within a single interaction (Artemyev et al., 2014; 2020a) (see Chapter 1.4.2.7.3 and Subsection 1.4.2.8). Since I_z determines the particle’s oscillation amplitude and thus its pitch angle, the destruction of I_z is physically equivalent to pitch-angle scattering—but through a “superfast” mechanism fundamentally distinct from, and potentially more efficient than, wave–particle resonance. Because current sheets are abundant throughout the heliosphere and their thickness overlaps with the gyro-radii of suprathermal and energetic ions, such interactions are not rare events but a systematic feature of SEP propagation.

Despite their importance, a quantitative understanding of how current sheets influence SEP transport has remained incomplete, for two reasons. First, the statistical properties of kinetic-scale current sheets—their occurrence rate, thickness distribution, and internal magnetic configuration—have not been systematically characterized across different regions of the heliosphere. Second, the connection between these microphysical structural properties and macroscopic transport coefficients has not been rigorously established. This dissertation addresses both gaps.

Specifically, this dissertation (1) develops a coherent observational framework to characterize the properties and occurrence rates of current sheets across heliocentric distances from 0.17 to 5 AU (Zhang et al., 2025a; 2026a), and (2) constructs a quantitative model of pitch-angle scattering and spatial transport of energetic particles driven by current sheets, parameterized by the observed statistical distributions (Zhang et al., 2025b). Together, these contributions bridge the microphysics of individual current sheet encounters and the macroscopic diffusion of energetic particles through the heliosphere, offering new insight into heliospheric particle dynamics and a foundation for improved space weather prediction.

1.2 Thesis Organization

The remainder of this chapter reviews the observational and theoretical background in two parts. Section 1.3 reviews the observational properties of solar wind current sheets, including identification and characterization methods, their kinetic nature, and the statistical characteristics reported in the literature. Section 1.4 introduces the solar energetic particle context: the sources and classification of SEP events, the transport frameworks within which pitch-angle scattering is parameterized, and the motivation—rooted in solar wind intermittency—for going beyond classical quasi-linear theory; it develops the quasi-adiabatic theory of particle motion near magnetic field reversals and the mechanisms by which the quasi-adiabatic invariant is destroyed at separatrix crossings.

The body of the thesis is then organized into two parts. **Part I** (Chapter 2 (Zhang et al., 2025a) and Chapter 3 (Zhang et al., 2026a)) presents the observational characterization of kinetic-scale current sheets across the inner heliosphere from a coordinated set of spacecraft: Parker Solar Probe (PSP) at distances as close as 0.17 AU, Wind, ARTEMIS, and STEREO near 1 AU, and Juno during its cruise phase out to 5 AU. These chapters systematically quantify the statistical distributions of current sheet thickness and current density—two parameters that directly determine the magnetic field configuration experienced by energetic particles. A central finding is that the normalized properties of current sheets (thickness in units of the ion inertial length, current density in units of the Alfvén current density) are largely invariant from 0.17 to 5 AU, implying that the scattering

environment for energetic particles maintains a consistent character throughout the inner heliosphere. The observational results therefore provide the empirical foundation for the particle-transport studies that follow.

Part II (Chapter 4 and Chapter 5) investigates how kinetic-scale current sheets scatter and transport energetic particles. Chapter 4 (Zhang et al., 2025b) develops an exact Hamiltonian formulation for particle motion in force-free current sheets and quantifies pitch-angle scattering through test-particle simulations parameterized by the observed distributions from Part I. The scattering is shown to be dominated by infrequent but large pitch-angle jumps—a non-Brownian process driven by geometrical chaotization—rather than continuous diffusion. Chapter 5 extends this analysis to spatial transport, showing that the perpendicular-to-parallel diffusion ratio increases with particle energy and can exceed standard quasi-linear predictions, with implications for the broad spatial distributions observed in SEP events. Together, these chapters bridge the microphysics of individual current sheet encounters and macroscopic heliospheric transport.

Chapter 6 summarizes the principal findings and discusses open questions and future directions, with emphasis on the origins of solar wind current sheets and on strategies for incorporating intermittency effects into SEP transport models.

Two appendices present complementary developments that support the main results. Appendix A (Zhang et al., 2026b) introduces a multi-fluid current sheet model developed to interpret the plasma velocity structure and sub-unity Alfvénicity observed in the current sheet catalogs of Part I; it is constructed to allow non-zero normal magnetic field components while maintaining constant magnetic field magnitude, thereby extending beyond simplified one-dimensional MHD configurations. Appendix B describes the Julia-based software ecosystem that underpins the large-scale statistical analyses and test-particle simulations performed throughout this work, enabling performant and interactive scientific exploration.

1.3 Observations of Solar Wind Current Sheets

This section reviews the observational landscape of solar wind current sheets (Khabarova et al., 2021; Neugebauer & Giacalone, 2010; Tsurutani & Ho, 1999), tracing their study from the earliest spacecraft measurements to the high-cadence, multi-point observations available today. The review is organized as follows: we begin by recounting how abrupt magnetic field rotations were first recognized as magnetohydrodynamic discontinuities and how subsequent high-resolution measurements revealed their fundamentally kinetic character. We then discuss the analysis methods used to determine current sheet orientation and thickness, with particular attention to the strengths and limitations of single-spacecraft and multi-spacecraft techniques. The bulk of the chapter is devoted to the statistical properties of current sheets — their identification, magnetic field configuration, spatial scales, current densities, occurrence rates, Alfvénicity, and orientation — as established by surveys spanning from the inner heliosphere to beyond 5 AU. Throughout, we emphasize the extent to which reported statistics depend on the identification method employed, a recurring theme that must be kept in mind when comparing results across studies. The section concludes by identifying several open questions that motivate the work presented in subsequent chapters.

1.3.1 From MHD Discontinuities to Kinetic-Scale Current Sheets

Early observations from the Pioneer 6 mission revealed that the direction of the IMF is highly variable, an unexpected finding at the time (Ness et al., 1966). As shown in Figure 1.4, on hour-long timescales, these abrupt directional changes are clearly distinguishable from the comparatively quiet background in which the magnetic field evolves slowly. Such rapid variations in the magneto-plasma parameters were recognized as fundamental solar wind features (Colburn & Sonett, 1966) and were identified as magnetohydrodynamic discontinuities—spatial boundaries separating two distinct plasma regions.

MHD theory permits such discontinuities but constrains the changes allowed across them through the Rankine–Hugoniot jump conditions. The early solar wind measurements spurred the development of theory for anisotropic plasmas (Hudson, 1970). Five distinct types are possible, the most relevant here being tangential discontinuities (TDs), rotational discontinuities (RDs), and shocks (relatively rare in the solar wind). Classifying observed

discontinuities as RDs or TDs attracted considerable early research interest because the distinction carries physical implications for the topology of the IMF (Knetter, 2005). A TD separates two topologically distinct plasma regions with no normal component, whereas an RD is a propagating structure that connects magnetically linked regions. This distinction has consequences for energetic particle diffusion coefficients and bears on possible generation mechanisms operating in the solar corona. The relative abundance of RDs and TDs in the solar wind has been the subject of longstanding debate (Neugebauer, 2006; Neugebauer et al., 1984; Smith, 1973).

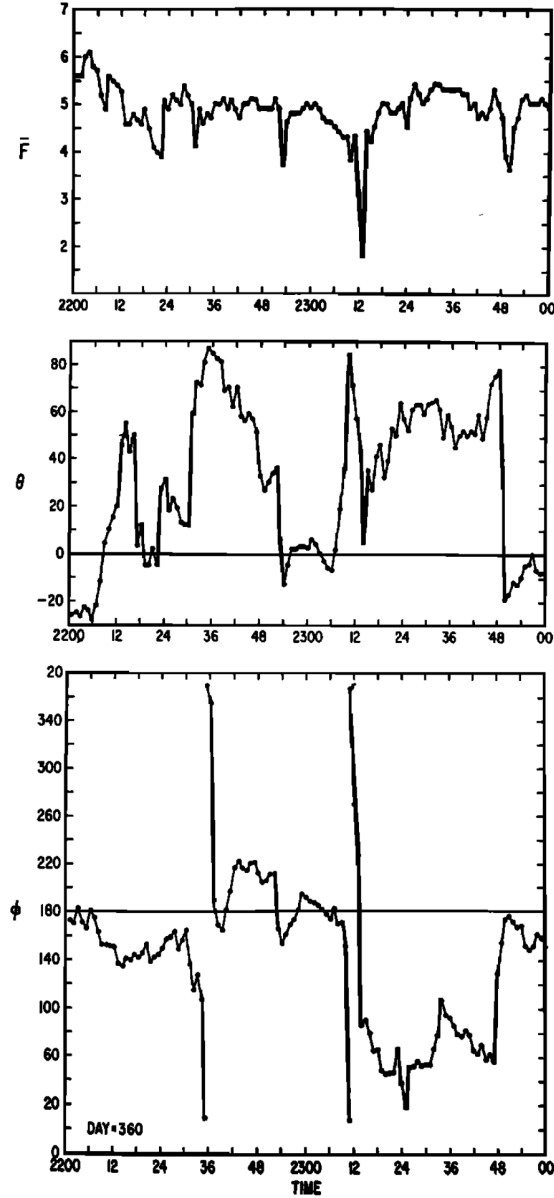


Figure 1.4: Two-hour example of 1-minute averages of the interplanetary magnetic field for which the magnitude is average, but the direction is highly variable and principally inclined at large angles ($\theta \approx 90^\circ$) to the ecliptic plane (Ness et al., 1966)

At smaller scales (on the order of seconds), many discontinuities retain their sharp character, though some reveal resolvable internal structure even in early measurements (Burlaga, 1969; Siscoe et al., 1968). At these scales, the term “discontinuity” becomes inappropriate: the structure width is comparable to the ion inertial length, and MHD theory may no longer be applicable. The term *current sheet* is adopted instead, emphasizing the current layer that maintains the field rotation. In this dissertation, we use “current sheet” throughout

to emphasize the kinetic nature of these structures. The kinetic scale generally refers to structures with widths comparable to the ion inertial length, corresponding roughly to temporal scales below 30 seconds at 1 AU. (Four scale regimes were introduced by Burlaga (1969): macro-scale (> 100 h), meso-scale (1–100 h), micro-scale (30 s – 1 h), and kinetic-scale (< 30 s).)

Recent observations from multiple missions have confirmed that many solar wind current sheets possess fundamentally kinetic properties that defy a purely MHD description (see Figure 1.5 for an example). Artemyev et al. (2019a) analyzed discontinuities observed by the ARTEMIS and MMS missions and found that these structures exhibit characteristics of both TDs and RDs simultaneously: tangential velocity jumps correlate well with Alfvén speed jumps (an RD signature), yet electron density and temperature vary significantly across them (a TD signature).

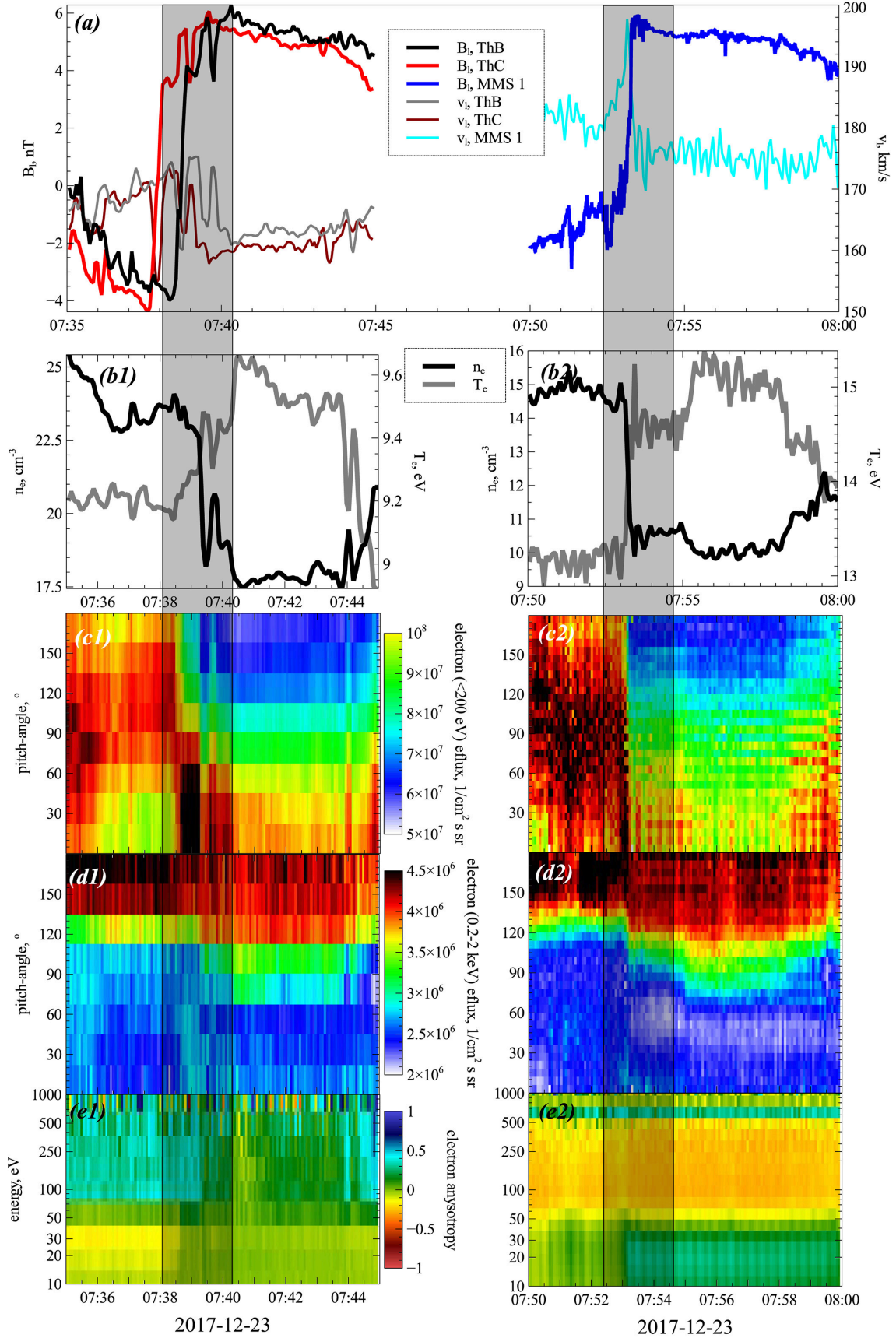


Figure 1.5: Discontinuity observations by two ARTEMIS (at $\sim 07:38:00$ and $\sim 07:38:30$) and the MMS 1 (at $\sim 07:53:00$) spacecraft. (a) The magnetic field B_l (left axis) and plasma velocity v_l (right axis). (b1 and b2) The electron density n_e (left axis) and temperature T_e (right axis). (c1, c2, d1, and d2) The electron pitch angle distributions for two energy ranges. (e1 and e2) The electron flux anisotropy.

Complementary statistical work by Artemyev et al. (2019b) using ARTEMIS data revealed that ion-scale discontinuities are accompanied by density and temperature variations extending over tens of ion inertial lengths. The inversely correlated density and temperature variations suggest a nearly force-free configuration. These structures exhibit two characteristic spatial scales: an intense inner current layer ($> 1 \text{ nA/m}^2$) enveloped by a broader outer structure. The magnetic field rotation occurs at the outer scale, while plasma pressure gradients provide pressure balance at the inner scale. The electron kinetic behavior around these structures is strongly energy-dependent: near-thermal electrons (10–30 eV) exhibit significant pitch-angle changes across the discontinuity, whereas hot electrons (100–1000 eV) retain their distribution properties on both sides, suggesting they can cross the structure freely.

Further insight into the kinetic nature of current sheets was provided by Artemyev et al. (2020b). Rotational discontinuities are typically accompanied by velocity jumps Δv_l that are systematically smaller than the corresponding Alfvén speed jumps Δv_A , contrary to the stationary MHD prediction of equality. Previous explanations invoked either pressure anisotropy reducing Δv_A or non-stationarity from residual magnetic energy. Artemyev et al. (2020b) proposed an alternative: nonadiabatic ion interactions with intense thin discontinuities produce nongyrotropic ion distributions with a nondiagonal pressure tensor component whose cross-discontinuity gradient reduces Δv_A . ARTEMIS observations confirmed the existence of such an ion population with sufficient amplitude and spatial profile to account for the discrepancy, demonstrating that ion kinetic effects fundamentally shape the internal structure of solar wind current sheets.

Consequently, investigating the formation, evolution, and particle interactions of current sheets requires moving beyond MHD theory and into the realm of ion and electron kinetics.

1.3.2 Analysis Methods: Normal Determination and the Planar Approximation

Solar wind current sheets are commonly approximated as one-dimensional structures in which the dominant variation occurs along the direction normal to the sheet. Under this approximation, the most important spatial parameter is the thickness—the scale over

which the magnetic field changes across the structure. Estimating the thickness requires knowledge of the current sheet normal, and the accuracy of this estimate depends critically on the method used to determine it. A detailed treatment and comprehensive review of both single-spacecraft and multi-spacecraft analysis techniques can be found in Knetter (2005). In this section, we do not attempt to reproduce that earlier review. Instead, we focus on developments that have emerged since then.

1.3.2.1 Single-Spacecraft Methods

For single-spacecraft observations, two methods are widely used. The first is minimum variance analysis (MVA) of the magnetic field, which identifies the direction of minimum magnetic field variance in the transition layer as the sheet normal, valid under the assumption that the normal component of the magnetic field is continuous (Sonnerup & Cahill Jr., 1967; Sonnerup & Scheible, 1998). The second is the cross-product method, which estimates the normal from the cross product of the upstream and downstream magnetic field vectors, and is valid under the assumption that the two vectors are coplanar, which can only be true if the normal component is zero (Burlaga & Ness, 1969; Wang et al., 2024).

MVA has been the most widely used technique in the literature, and much of the global statistical picture of solar wind discontinuities has been built upon it. A key advantage of MVA is that it makes no a priori assumption about the magnetic field geometry—it can in principle recover the normal direction for both TDs and RDs. The method is designed to handle realistic deviations from an ideal one-dimensional layer—including 2D or 3D internal structure, temporal fluctuations in normal orientation, and measurement uncertainties—provided there is no systematic change in the normal direction during the spacecraft traversal (Sonnerup & Scheible, 1998). In practice, however, these non-ideal effects can be severe enough to cause MVA to fail. Systematic comparisons with multi-spacecraft determinations have revealed that MVA can be inaccurate for solar wind current sheets. Horbury et al. (2001), using three-spacecraft timing with Geotail, Wind, and IMP-8, found that many MVA normal estimates lie far from the timing-derived normals. In their dataset, 77% of events were likely TDs based on timing, yet single-spacecraft MVA would have classified a much larger fraction as RDs—a discrepancy they attributed partly

to surface waves on the discontinuities (which may cause the derived minimum variance directions to be approximately perpendicular to discontinuity normals).

The nature of these MVA failures has been clarified by subsequent work. Teh et al. (2011), applying Grad–Shafranov reconstruction (based on the ideal 2D MHD equations in steady state) to Cluster observations, showed that internal structures such as magnetic islands (flux ropes) within the transition layer can cause MVA to fail as a predictor of the normal direction. Since MVA assumes a planar, one-dimensional geometry, any two-dimensional substructure may shift the minimum variance direction away from the true normal. (Good agreement with timing methods can be achieved by imposing the additional constraint $\langle B_N \rangle = 0$ on MVA, though this predetermines the TD nature of the structure.) Liu et al. (2023) conducted a comprehensive statistical assessment using 6,752 Cluster discontinuities with timing-derived normals as a benchmark. They found that while increasing the eigenvalue ratio λ_2/λ_3 and narrowing the analysis window can reduce scatter, MVA suffers from an inherent geometric defect: discontinuities with small normal magnetic field component ($|B_N|/|B| < 0.2$) and small magnitude change ($\Delta|B|/|B| < 0.05$) are systematically misidentified. In these cases, MVA confuses the dominant in-plane magnetic field component with the normal component, producing a spurious large $|B_N|$ and an apparent in-plane rotation angle of $\sim 180^\circ$. This mechanism causes genuine TDs to be misclassified as RDs with dominant normal fields, explaining the false RD predominance reported in many earlier MVA-based studies. Despite these limitations, Liu et al. (2023) showed that MVA can achieve acceptable accuracy under favorable geometric conditions. Since the magnitude change $\Delta|B|/|B|$ and the rotation angle ω do not depend on knowledge of the normal and are known a priori from the asymptotic values far from the discontinuity, they can serve as pre-selection criteria: MVA errors remain generally below 30° when either $\Delta|B|/|B| > 0.05$ or $\omega > 60^\circ$. The problematic population is therefore confined to small-angle, nearly constant-magnitude current sheets.

The cross-product method, by contrast, has been shown to be substantially more accurate. Wang et al. (2024), comparing single-spacecraft estimates against four-spacecraft Cluster timing for 1,831 current sheets, demonstrated that the cross-product normal agrees with the timing normal to within 15° at the 90% confidence level, whereas MVA normals frequently deviate by more than 60° —likely due to contamination by *anisotropic* turbulent

fluctuations. Combined with the Taylor frozen-in hypothesis (validated by the finding that current sheet propagation velocities agree with local ion flow velocities within $\sim 20\%$), the cross-product method delivers current sheet thickness and current density amplitude within 20% of their multi-spacecraft values at the 90% confidence level. However, the cross-product method has an important limitation: it assumes a vanishing normal magnetic field component ($B_N = 0$), which is strictly valid only for tangential discontinuities. For structures with a significant normal field component, the cross product of the asymptotic fields does not coincide with the true normal. In practice, this limitation is mitigated by the observational finding that the vast majority of kinetic-scale current sheets have very small $|B_N|/|B|$ (Erdős & Balogh, 2008; Wang et al., 2024), making the assumption a good approximation for the bulk of the population. This single-spacecraft methodology has been widely adopted in recent statistical studies of kinetic-scale current sheets (Lotekar et al., 2022; Vasko et al., 2021; 2022; 2024).

Erdős & Balogh (2008) reached a partially reconciling conclusion from the Ulysses dataset: for the subset of well-defined discontinuities with reliable normals, MVA and the cross-product technique yield consistent results. They advocated retaining only such well-defined events for further analysis, noting that the vast majority of these have a small magnetic field component parallel to the normal. The practical implication is that MVA can be used reliably when applied judiciously with appropriate quality filters, but its unconstrained, casual application to the full population of discontinuities introduces systematic biases that have historically distorted the statistical picture—particularly the RD/TD classification.

1.3.2.1.1 Multi-Spacecraft Methods and Higher-Dimensional Structure

Multi-spacecraft observations have played a crucial role in advancing our understanding of current sheets, as they allow improved determination of the normal direction and direct separation of spatial structure from temporal evolution (Horbury et al., 2001; Knetter, 2005; Knetter et al., 2003; 2004; Ness, 1966). The timing method compares the arrival times of the same structure at several spacecraft with known relative positions, enabling geometric inference of the sheet orientation and propagation velocity (Knetter, 2005; Paschmann & Daly, 2000; 2008; Vogt, 2020). Missions such as Cluster and MMS have greatly expanded the use of these techniques.

Beyond providing more accurate normals, multi-spacecraft observations have revealed that many solar wind current sheets are not perfectly planar. Lepping et al. (2003), using Wind and IMP-8 data for 134 large-angle ($\omega > 90^\circ$) discontinuities, estimated a weighted-average radius of curvature of $\sim 380 R_E$ (with a most probable value of $\sim 290 R_E$; however, their analysis is unable to distinguish real curvature from shorter-scale surface variations using only two-spacecraft data sets), and an average thickness of $\sim 14 R_E$ (most probable $\sim 6 R_E$). These results caution against the simplistic use of the planar assumption when projecting a distantly observed discontinuity to predict its arrival characteristics at a downstream location. Malaspina & Gosling (2012), exploiting the variable separation of the twin STEREO spacecraft, studied tens of thousands of discontinuities and found that the distributions of thickness, normal orientation, shear angle, and waiting times differ systematically between discontinuities observed by both spacecraft and those seen by only one. The population observed by both spacecraft—those with sufficient lateral extent to be intercepted at two separated points—was most consistently interpreted as the walls of solar wind flux tubes.

Söding & Neubauer (1999) proposed a method to determine the orientation and propagation velocity of two-dimensional structures using two-spacecraft data under the assumption of a steady-state, divergence-free magnetic field. While no clear 2D structures were identified on the ~ 10 -hour scales examined with Wind and IMP-8, the method established a framework for probing departures from planarity at smaller scales. Teh et al. (2011) subsequently demonstrated with Grad–Shafranov reconstruction that directional discontinuities can contain internal magnetic islands, making them irreducible to simple TD or RD classifications and underscoring the importance of accounting for multidimensional geometry when interpreting spacecraft crossings.

1.3.3 Statistical Surveys and Identification Methods

Following the initial discovery of solar wind current sheets, research shifted toward systematic statistical surveys (Neugebauer & Giacalone, 2010; Tsurutani & Ho, 1999). This section reviews general statistical properties and the methods used to identify current sheets. Parameters central to understanding both their physical nature and their dynamical influence on energetic particles — magnetic field configuration, spatial scale

(Subsection 1.3.3.4), and occurrence rate (Subsection 1.3.3.3) — are discussed in the subsequent sections.

A key point that must be emphasized at the outset is that statistical properties depend critically on the identification method. Different selection criteria—thresholds on magnetic field rotation angle, magnetic field increments, partial variance of increments (PVI), or relative standard deviation—introduce systematic biases into the sampled population. Methods optimized for large-amplitude, well-defined discontinuities preferentially select broader, MHD-scale structures, whereas gradient-based or increment-based approaches are more sensitive to thinner, kinetic-scale current sheets. Reported distributions of thickness, current density, and occurrence rate are therefore inherently method-dependent, and care must be taken when comparing results across studies.

To process the vast amounts of spacecraft data, various automated identification algorithms have been developed. Table 1.1 summarizes the primary quantitative criteria utilized in the literature.

Table 1.1: Summary of current sheet identification methods used in the literature.

Method	Description	Method Reference	Applications
Directional change	Change in the direction of $\mathbf{B}$	Burlaga (1969)	Söding et al. (2001)
Relative field change	Relative change in magnetic field $\mathbf{B}$	Tsurutani & Smith (1979)	Söding et al. (2001)
Correlation / angle distribution	Two-time correlation functions and distribution of angle change over a time lag	Li (2007)	Li et al. (2008)
PVI	Partial Variance of Increments	Greco et al. (2017)	Vasko et al. (2021); Vasko et al. (2022); Vasko et al. (2024)
Relative standard deviation	Relative standard deviation of $\mathbf{B}$	Liu et al. (2022b)	Zhang et al. (2025a)

Most early statistical studies focused on large-scale or mesoscale current sheets that are readily identifiable in lower-cadence data. While these works provide essential context, their results cannot be directly compared with statistics derived from high-cadence measurements targeting kinetic-scale structures. Differences in scale selection, detection thresholds, and instrumental resolution introduce subtleties that must be carefully navigated. For instance, as demonstrated by Vasquez et al. (2007), current sheets become exponentially more numerous at smaller spread angles, a population often missed by earlier methods which focus on isolated, large-angle events and exclude structures in close proximity to one another. Therefore, while prior studies inform the broader landscape, the results presented in this thesis pertain specifically to the kinetic-scale population and should be interpreted within the framework of the identification methodology employed herein.

1.3.3.1 Small Intensity jump, $\Delta|B|$

While it is possible for a current sheet to exhibit a large jump in magnetic field magnitude, the vast majority are predominantly characterized by a rotation of the magnetic field across the sheet, with the magnitude remaining nearly constant. This was first recognized by Burlaga (1969), who observed that most sharp changes in the IMF are primarily directional and introduced the term *directional discontinuity* (DD). Quantitatively, the change in $|B|$ is less than 20% for approximately 75% of the discontinuities in their study.

More recent high-resolution analyses confirm this near-constant magnitude at smaller scales. Using 1/3-second resolution ACE data, Vasquez et al. (2007) found that most discontinuities have ramp-like internal profiles—the field varies nearly monotonically within the layer, with no evidence of rapid compression or dissipation (Tsurutani et al., 2005). Furthermore, the intensity jump distribution for solar wind discontinuities is best fit with a lognormal function and is narrowly confined about unity, in contrast to the much broader distribution found in phase-randomized surrogate fields. This difference implies that the layer is regulated by specific physical processes (e.g., nonlinear wave magnetic pressure and Landau damping) rather than random superposition of fluctuations.

This conclusion is further reinforced by Lotekar et al. (2022) and Vasko et al. (2024), who analyzed 11200 proton kinetic-scale current sheets near the sun by Parker Solar Probe and 16903 current sheets at 5 AU observed by Ulysses. The magnetic field rotates through a

shear angle with only weak magnitude variation. The maximum variation of $|B|$ within a current sheet is statistically larger than the variation between its boundaries, and larger magnitude variations are typical at higher plasma β (Figure 1.6).

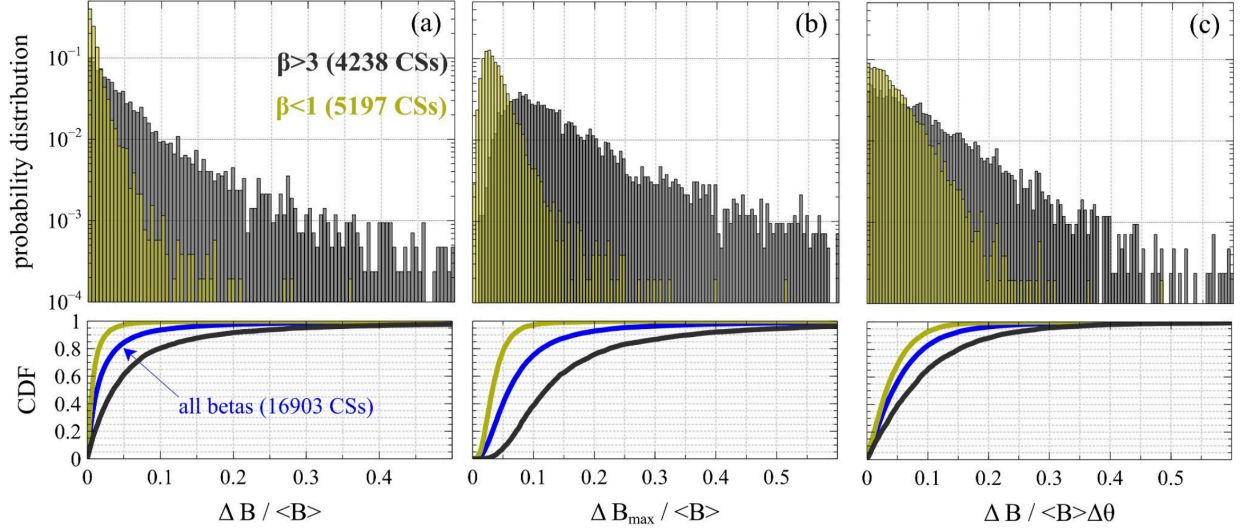


Figure 1.6: Probability and cumulative distributions of parameters $\Delta B/\langle B \rangle$, $\Delta B_{\max}/\langle B \rangle$ and $\Delta B/\langle B \rangle \Delta \theta$ for subsets of the current sheets (CSs) observed at different plasma betas, $\beta < 1$ and $\beta > 3$. The bottom panels also present the cumulative distributions corresponding to all the CSs in our data set. Note that parameter $\Delta B/\langle B \rangle \Delta \theta$ quantifies the ratio between average perpendicular and parallel current densities within CS.

1.3.3.2 Field Rotation Angle

The field rotation angle ω (also referred to as the spread angle, shear angle, or directional change) is one of the most fundamental parameters characterizing current sheets. Its distribution depends on the statistical ensemble (i.e., the identification criteria), solar activity level, radial distance from the Sun, and the type of discontinuity. A robust finding across all studies is that discontinuities become more abundant at smaller spread angles.

Burlaga (1969) first showed that the number of discontinuities falls off rapidly with increasing ω . Subsequent studies confirmed this behavior and characterized the distribution quantitatively [Burlaga (1971a); Burlaga (1971b); Mariani et al. (1973);]. For $\omega \geq 30^\circ$, the distribution is well described by $N(\omega) \propto \exp[-(\omega/\omega_s)^2]$, where the scale parameter ω_s encodes the characteristic width of the distribution. Burlaga (1969) found $\omega_s = 75^\circ$ during a solar minimum period (December 1965–January 1966), while Mariani et al. (1973) obtained a significantly smaller $\omega_s = 44^\circ$ during a period of higher solar activity. This

difference likely reflects a dependence on solar cycle phase (Mariani et al., 1973). Knetter (2005), using our coordinated spacecraft (Cluster) for four different periods between 2001 and 2003, further demonstrated that ω depends on solar wind type: the spread angle tends to be smaller in slow solar wind from active regions and larger in fast solar wind originating from coronal holes.

Extending the analysis to small rotation angles, Vasquez et al. (2007) showed that the small-spread-angle population forms a smooth continuation of the larger-angle distribution, which is best fit by a *lognormal* function. For most discontinuities, the maximum spread angle within the layer is nearly equal to the net edge-to-edge value, confirming that the field rotation is approximately monotonic across the structure. This finding was subsequently cited by Neugebauer & Giacalone (2010) as evidence that the method of Vasquez et al. (2007) captures a previously unexamined but physically continuous population.

A radial dependence of ω_s was established by Söding et al. (2001), who found that the distribution steepens with increasing heliocentric distance: ω_s decreases from $\sim 82^\circ$ to $\sim 50^\circ$ between the inner heliosphere and several AU (see Figure 1.7). Fewer events with $\omega > 60^\circ$ are observed at larger distances, indicating that discontinuities evolve during their outward propagation. Whether this evolution leads to eventual annihilation of current sheets remains unclear. Notably, the radial dependence of ω_s differs depending on the identification criterion: it is present for the Tsurutani–Smith (TS) criterion but absent for the Burlaga (B) criterion inside 2.3 AU, suggesting that the evolution is driven by the additionally identified population of anisotropic RDs. For TDs alone, the mean rotation angle $\langle \omega \rangle \approx 78^\circ$ shows no radial dependence, whereas for RDs, smaller ω is more probable and fewer large- ω events survive at greater distances.

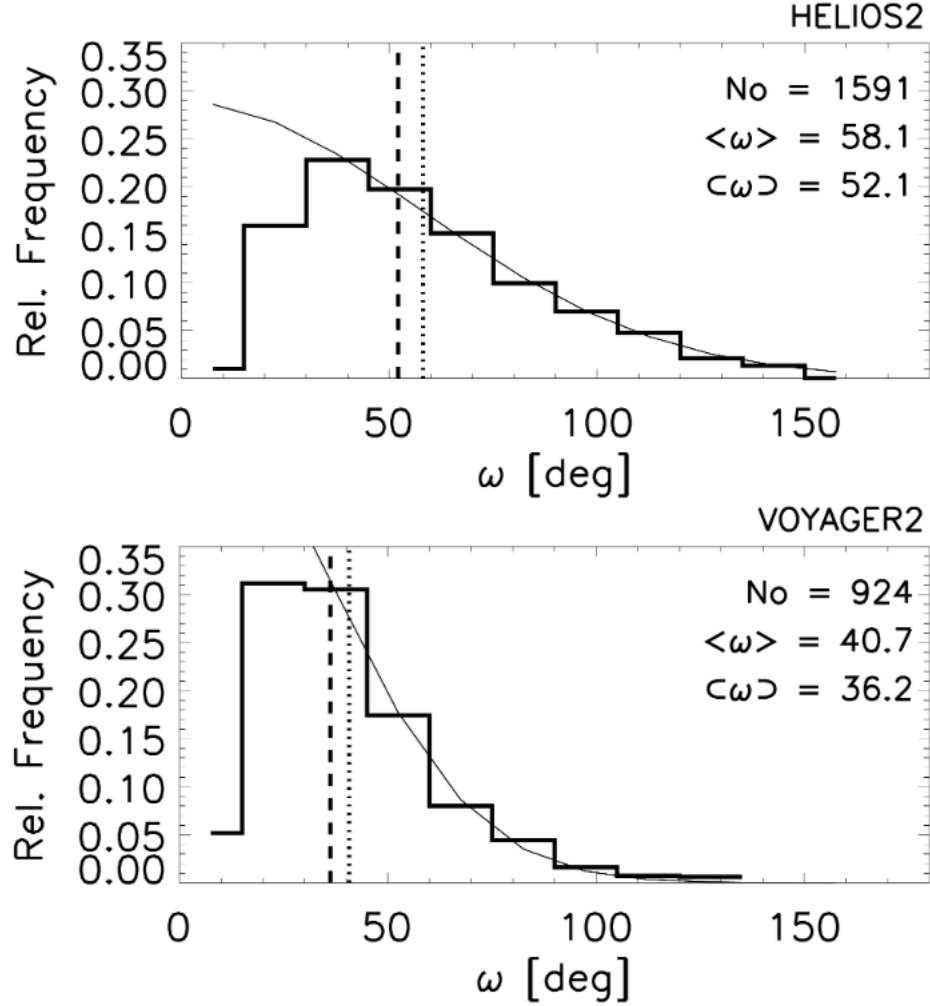


Figure 1.7: Relative frequency of ω for Helios 2 (top) and Voyager 2 (bottom) as a histogram; thin solid line is a fit to the distribution proportional to $\exp[-(\omega/\omega_s)^2]$

1.3.3.3 Occurrence rate

The occurrence rate of current sheets is important from both plasma-physics and particle-transport perspectives. From the standpoint of solar wind physics, occurrence statistics constrain the generation mechanisms of current sheets—including their relation to turbulence intermittency, flux-tube boundaries, and large-scale solar wind structuring—and provide information about their stability and evolution during outward propagation. From the standpoint of energetic particle transport, the frequency with which particles encounter current sheets determines the cumulative scattering rate and therefore influences large-scale diffusion properties in both momentum and configuration space.

A central question is whether current sheets are formed close to the Sun and subsequently convected outward by the solar wind, or whether they are generated in situ at all heliocentric distances, for example in colliding solar wind streams. As summarized by Knetter et al. (2003), early radial surveys spanning approximately 0.3 to 10 AU consistently reported a decrease in occurrence rate with increasing radial distance. However, interpreting this trend is not straightforward. The observed decrease may indicate genuine disintegration of current sheets during their outward propagation. Alternatively, it could reflect a changing balance between local generation and destruction processes. It may also arise from observational effects: as structures evolve, their orientation relative to the radial direction may change, reducing the locally detected occurrence rate. In addition, current sheets may thicken with increasing distance, causing them to fall below instrumental detection thresholds and thereby introducing an observational bias (Lepping & Behannon, 1986).

The earliest radial studies established the basic phenomenology. Burlaga (1971b), using Pioneer 6 data, found that the occurrence rate at 0.82 AU is only slightly lower than at 1 AU (“this may be due to the lower data quality and increase in the number of data gaps when the spacecraft is far from the earth”), and that the distributions of rotation angle and discontinuity normals are very similar across the range 0.8–1.0 AU. This suggested that most discontinuities originate inside 0.8 AU and do not evolve appreciably over this distance range. Importantly, the occurrence rate in regions of increasing bulk speed was only slightly higher than elsewhere, arguing against stream collision as the primary generation mechanism. Mariani et al. (1973), analyzing over 16,000 events from Pioneer 8, reported an average occurrence rate of approximately 3.6 per hour near 1 AU (with ~ 1.6 per hour identified as TD-like) and found a correlation with the directional change ω and a decrease with increasing heliocentric distance. However, they also noted a possible dependence on heliographic latitude.

Tsurutani & Smith (1979) made a major contribution by using simultaneous Pioneer 10 and 11 data to separate spatial from temporal variations. This distinction was essential, as occurrence rates display substantial day-to-day and solar-rotation-scale fluctuations well outside *Poisson* expectations. They found that the rates averaged over Bartels rotations were strongly correlated between the two spacecraft despite their ~ 2 AU separation, and that the statistical properties of discontinuities at 1 and 5 AU were remarkably similar.

Both findings support a scenario in which discontinuities originate within 1 AU and are subsequently convected outward by the solar wind. The radial dependence of the occurrence rate follows $\rho = 50 e^{-(R-1)/4}$ per day, corresponding to an apparent decrease of about 25% per AU. However, they argued that this radial gradient may not represent true physical decay: it could arise from progressive thickening of current sheets such that they no longer satisfy identification criteria. Finally, they demonstrated that temporal variations, persisting over several months, had likely been misinterpreted as latitudinal gradients in earlier Pioneer 8 results (Mariani et al., 1973).

The picture was enriched by Ulysses observations at high heliographic latitudes. Tsurutani et al. (1996) found a radial decrease from 1 to 5 AU following $e^{-(r-1)/5}$. More strikingly, the occurrence rate increased by a factor of ~ 5 as Ulysses moved from Jupiter at 5 AU to 2.5 AU over the south pole (from the ecliptic plane to -80° heliographic latitudes), with a one-to-one correspondence between high occurrence rates and high-speed streams from coronal holes. In these streams, nonlinear outward-propagating Alfvén waves with large transverse fluctuations are ubiquitous, and rotational discontinuities frequently form the edges of phase-steepened Alfvén waves—offering a natural explanation for the elevated occurrence rates.

Söding et al. (2001) synthesized data from five missions spanning 0.3–19 AU and -80° to $+10^\circ$ latitude during solar minimum. They found that the occurrence rate depends linearly on solar wind velocity (a geometric effect: faster wind sweeps more plasma volume past the spacecraft per unit time) and decreases radially as $r^{-0.78}$ (TS criterion) or $r^{-1.28}$ (B criterion). After normalizing to 400 km/s and 1 AU, approximately 64 discontinuities per day were identified with both criteria, and no residual dependence on heliographic latitude or solar wind structure type was observed—indicating that current sheets are uniformly distributed on spherical shells. Nonetheless, large day-to-day variations persisted even after normalization. The RD-to-TD ratio depended on solar wind structure, with relatively more RDs in high-speed streams, but showed no radial or latitudinal dependence in the inner heliosphere ($r < 10$ AU).

Vasquez et al. (2007), using their method sensitive to small-spread-angle events, found dramatically higher rates than earlier surveys: an average exceeding 243 per day for all

discontinuities, 117 per day above 15° , and 52 per day above 30° (comparable to the ~ 30 per day above 30° reported by classical methods). These rates exhibit pronounced temporal variability on both daily and hourly timescales, and discontinuities occur in spatial groupings with *lognormally* distributed separations. Even excluding active periods (interplanetary shocks, solar ejections), the rates were only weakly correlated with solar wind speed.

A methodological subtlety that pervades all occurrence rate studies was highlighted by Erdős & Balogh (2008), who used the extensive Ulysses magnetometer dataset to critically examine the role of the identification method. They showed in Figure 1.8 that occurrence rates differ dramatically depending on whether events are selected by their temporal rate of change (in the spacecraft frame) or by their spatial gradient (transformed into the solar wind frame): the temporal criterion systematically overestimates the number of discontinuities in fast solar wind, because structures convect more rapidly past the observer. After correcting for this bias, they confirmed the radial decrease in spatial density with increasing distance from the Sun. And surprisingly, they found that at a given radial distance, periods with slower solar wind tended to contain more discontinuities.

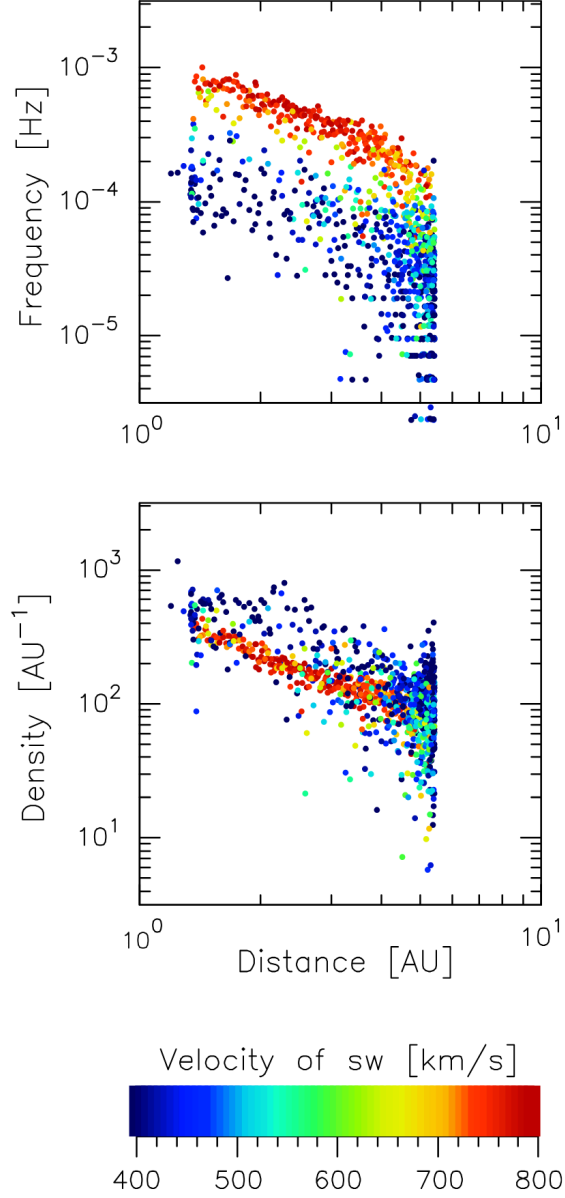


Figure 1.8: The number of discontinuities as a function of the distance from the Sun (horizontal scale) and the velocity of solar wind (color coded). Upper panel: selection of events by time rate of change. Lower panel: selection of events by spatial gradients.

Recent inner-heliosphere measurements from Parker Solar Probe and Solar Orbiter have extended these statistics closer to the Sun than previously possible. Liu et al. (2021) analyzed 3,948 discontinuities between 0.13 and 0.9 AU and found a steep radial decrease following $r^{-2.00}$. A particularly interesting finding was that the RD occurrence rate decreases more steeply ($r^{-2.17}$) than the TD rate, so that the RD-to-TD ratio drops sharply from ~ 8 at $r < 0.3$ AU to ~ 1 at $r > 0.4$ AU, exhibiting distinct evolution with distance.

Madar et al. (2024), combining Solar Orbiter and Parker Solar Probe data, identified over 140,000 discontinuities between 0.06 and 1.01 AU and confirmed the power-law decrease in spatial density, fitting an exponent of -0.93 —somewhat shallower than the $r^{-2.00}$ of Liu et al. (2021), likely reflecting differences in identification criteria and the correction for solar wind velocity effects. They identified several competing mechanisms that shape the radial profile: the increasing Parker spiral angle with distance affects how many TD-like flux-tube boundaries are swept past the spacecraft; the smaller cross-section of flux tubes near the Sun makes boundary crossings more probable; and any radial evolution of current sheet thickness introduces selection biases for gradient-based detection methods.

Taken together, these studies establish that current sheet occurrence rates decrease with heliocentric distance, but the precise radial scaling depends sensitively on identification criteria and the population of discontinuity types sampled with corrections for solar wind velocity effects. The much higher rates found by methods sensitive to small rotation angles (Vasquez et al., 2007) underscore that the total population of current sheets is substantially larger than suggested by classical surveys restricted to large-angle events. The differential radial evolution of RDs and TDs points to fundamentally different origins and lifetimes for these two populations—a distinction with direct implications for understanding how they are generated and sustained by solar wind turbulence.

1.3.3.4 Spatial Scale and Current Density

In the classical MHD framework, current sheets are treated as infinitely thin discontinuities—mathematical step functions across which plasma parameters change instantaneously. In reality, however, the transition between upstream and downstream regions occurs over a finite thickness, requiring a treatment beyond the MHD approximation. The impact of a current sheet on the plasma—and specifically on the dynamical process of particles within the sheet (Yamada et al., 2010)—is fundamentally governed by this spatial scale (Sergeev et al., 1990) and the associated internal current density (the ratio between gyroradius and the characteristic scale of magnetic inhomogeneity). These two closely coupled parameters (usually compared to local proton inertial length and Alfvén current density) dictate the transition from fluid-like MHD behavior to kinetic physics and are therefore central to understanding the role of current sheets in both turbulence dissipation and particle transport.

The thickness of a current sheet determines the physical regime in which the structure operates. The critical threshold occurs when the thickness approaches fundamental kinetic length scales: the ion inertial length $d_i = c/\omega_{pi}$ or the thermal ion gyroradius ρ_i . When $\lambda \sim \rho_i$, the assumptions of ideal MHD break down: ions become demagnetized within the sheet while electrons—with their much smaller gyroradius—remain magnetized. Test particle simulations reveal the kinetic consequences of this intermittent structure: Dmitruk et al. (2004) found that the current sheets spontaneously formed by MHD turbulence produce differential energization, with electrons developing large parallel velocities within current sheets while protons are energized preferentially in the perpendicular direction by nonuniform electric fields varying on proton kinetic scales. This differential response generates Hall electric fields and enables the onset of collisionless magnetic reconnection, which requires current sheet thicknesses comparable to d_i to proceed at sufficiently fast rates. Cassak et al. (2006) showed that as a Sweet–Parker dissipation region dynamically thins during reconnection, a critical transition occurs when its width drops below d_i : the Hall effect becomes dominant, the resistive MHD solution ceases to exist, and the system transitions abruptly to fast collisionless reconnection with rates orders of magnitude higher. Papini et al. (2019) extended this picture by investigating the tearing instability in both the MHD and Hall-MHD regimes. They showed that when a current sheet achieves a sufficiently small aspect ratio ($a/L \sim S^{-1/3}$ for Lundquist number $S \gg 1$), reconnection proceeds on ideal Alfvén timescales independent of S . In the nonlinear phase, secondary current sheets spontaneously form and, at high S , naturally adjust to this critical aspect ratio, driving very rapid reconnection. When the Hall term is included—appropriate once the resistive layer width δ becomes comparable to d_i —the secondary reconnection rate is enhanced by up to a factor of two relative to the pure MHD case and up to ten times faster than the linear phase, leading to explosive energy release on super-Alfvénic timescales.

The interplay between reconnection and the turbulent cascade is now recognized as fundamental (Boldyrev & Loureiro, 2019; 2020). In dynamically aligned Alfvénic turbulence, magnetic fluctuations naturally form progressively thinner sheet-like structures at smaller scales (Boldyrev, 2006). Analytic theories predict that below a critical thickness these sheets become tearing-unstable, disrupting the classical cascade. Mallet et al. (2017) calculated the disruption scale λ_D at which this onset occurs in a low- β collisionless plasma, showing that λ_D can exceed the ion sound scale ρ_s and produce a spectral

break at λ_D rather than at ρ_s , with a steepened “transition range” between them—a feature sometimes observed in solar wind turbulence intervals. Boldyrev & Loureiro (2017) proposed a complementary picture in which the tearing instability modifies the effective alignment of field lines, balancing the eddy turnover rate at all scales below the critical threshold and yielding a reconnection-mediated energy spectrum steeper than the classical prediction. These theoretical expectations have been confirmed numerically. Dong et al. (2018), in high-resolution 2D MHD simulations at magnetic Reynolds number $R_m = 10^6$, showed that the combined effects of dynamic alignment and turbulent intermittency produce copious plasmoid formation in intense current sheets; the resulting disruption steepens the energy spectrum toward a spectral index near -2.2 , consistent with the analytic predictions. Dong et al. (2022) extended this to three dimensions, demonstrating that rapid reconnection breaks elongated current sheets into chains of plasmoids and opens a previously unrecognized range of energy cascade in which the transfer rate is controlled by plasmoid growth, again producing a -2.2 spectral index accompanied by modified turbulence anisotropy. Franci et al. (2017), using high-resolution hybrid-kinetic simulations that retain ion kinetic effects, provided further confirmation: reconnection at current sheets with $a \simeq d_i$ actively drives the sub-ion-scale cascade, generating a stable power-law spectrum below the ion break as soon as the first reconnection events occur—regardless of the state of the large-scale cascade. Taken together, these results establish that current sheets at kinetic scales actively shape the turbulence spectrum, mediate the energy cascade across the ion break, and control the pathway by which magnetic energy is ultimately converted into particle heating.

For energetic particle transport, the spatial scale is equally decisive. When particles encounter a broad MHD-scale structure ($\lambda \gg \rho_{\text{SEP}}$), their motion remains adiabatic and they smoothly follow guiding-center trajectories. When $\lambda \sim \rho_{\text{SEP}}$, however, the magnetic field changes too abruptly for adiabaticity to be maintained, leading to strong pitch-angle scattering, temporary trapping, or reflection. The implications of this resonance condition for SEP transport will be examined in detail in the following sections.

Current density is inextricably linked to spatial scale through Ampère’s law: $\mathbf{J} = \nabla \times \mathbf{B}/\mu_0$. A thin magnetic field rotation necessarily implies an intense current layer. In the context of magnetic turbulence, the energy cascading from large to small scales is not

dissipated uniformly but is concentrated within coherent structures—predominantly thin, high-current-density sheets. Numerical simulations have quantified this intermittency in detail. Zhdankin et al. (2013), analyzing current sheets in driven reduced-MHD turbulence, found that structures with peak current density exceeding eight times the rms value occupy less than 1% of the simulation volume yet account for more than 25% of all Ohmic dissipation. They also showed that while not all intense current sheets contain magnetic X-points (about 55% do not), the most intense structures are preferentially reconnecting ones, with the probability of containing an X-point rising to $\sim 90\%$ for the strongest events.

Spacecraft observations corroborate this picture. Current sheets are correlated with enhanced electron and ion temperatures (Osman et al., 2011), and these structures, while constituting only $\sim 19\%$ of the data, can account for $\sim 50\%$ of the total plasma internal energy (Osman et al., 2012). If reconnection is triggered within an intense current sheet, the contracting magnetic islands can further accelerate particles to high energies. Recent Parker Solar Probe observations have provided direct evidence of proton acceleration up to ~ 400 keV within the reconnection exhaust of the heliospheric current sheet at $\sim 16 R_{\odot}$ (Desai et al., 2025).

Understanding how thickness and current density of current sheets evolve with heliocentric distance is therefore crucial for revealing their role in the thermodynamics of solar wind turbulence and dynamics of energetic particles: whether these structures maintain their kinetic-scale character and whether their current density weakens in tandem with the radial drop in magnetic field constrains theories of their local generation, evolution, and overall contribution to energy dissipation and particle transport throughout the heliosphere.

1.3.3.4.1 Thickness

The earliest thickness estimates, necessarily limited by instrumental resolution, revealed structures with spatial scales of thousands of kilometers or tens of proton inertial lengths (Burlaga, 1969).

The radial evolution of current sheet thickness was first systematically studied by Söding et al. (2001), who analyzed discontinuities from five missions spanning 0.3–19 AU. They found that the mean thickness in kilometers increases with heliocentric distance, as expected from the radial decrease in magnetic field strength and the associated expansion of kinetic

length scales. However, when normalized to the local proton gyroradius, the thickness decreases dramatically—by a factor of ~ 50 , from $\langle d_{\rho_g} \rangle \approx 201 \rho_g$ at 0.3 AU down to $\langle d_{\rho_g} \rangle \approx 4.3 \rho_g$ at 19 AU. A similar decrease, from $127 d_i$ to $2.6 d_i$, was found when normalizing to the ion inertial length. RDs were consistently thicker than TDs by a factor of ~ 1.5 . This strong radial thinning in normalized units indicates that current sheets do not simply expand passively with the solar wind but evolve dynamically, progressively approaching kinetic scales at larger distances.

Parker Solar Probe has extended these measurements into the pristine inner heliosphere. Liu et al. (2021), analyzing discontinuities between 0.13 and 0.9 AU, found distinct behavior for the two types: TD thicknesses normalized by d_i show no clear spatial scaling and range broadly from 5–35 d_i , whereas RD thicknesses decrease as $r^{-1.09}$ in normalized units. In absolute terms, the average RD thickness of ~ 574 km changes little with distance, implying that the normalized thinning reflects the radial increase of d_i itself. Madar et al. (2024), using combined Solar Orbiter and PSP data from 0.06 to 1.01 AU, reported a more nuanced picture: RD thickness first *decreases* between 0.06 and 0.30 AU, then increases beyond 0.30 AU in proportion to the local ion inertial length. TD thickness, by contrast, scales with d_i throughout the entire distance range. The authors interpreted these trends as evidence for different physical origins of the two types of discontinuities. RDs are thought to arise from the nonlinear steepening of Alfvén waves, a process that tends to generate structures with a significant magnetic-field component normal to the discontinuity surface. As the steepening progresses, the characteristic thickness decreases until it approaches ion kinetic scales, where dispersive and kinetic effects limit further steepening. TDs, on the other hand, are more likely associated with boundaries between magnetic flux tubes, whose widths tracks the local kinetic scale.

High-cadence measurements have made it possible to resolve the kinetic-scale population directly. Vasko et al. (2022), using Wind data at 11 samples/s, characterized 17,043 current sheets at 1 AU with thicknesses from a few tens to $\sim 1,000$ km, corresponding to $\$0.1\text{--}10 \lambda_p$ with typical values around 100 km ($\sim$ a few λ_p). Near the Sun, Lotekar et al. (2022) analyzed 11,200 current sheets around PSP’s first perihelion, finding thicknesses from a few to ~ 200 km (typical value ~ 30 km), or $\$0.1\text{--}10 \lambda_p$ with a typical value of $\sim 2 \lambda_p$. At 5 AU, Vasko et al. (2024) found half-thicknesses of 200–2,000 km for non-bifurcated

current sheets and 500–5,000 km for bifurcated ones, corresponding to $0.5\text{--}5 \lambda_p$ and $0.7\text{--}15 \lambda_p$ respectively. Despite the enormous difference in absolute scale across these distances, the remarkable consistency in normalized thickness—typically a few proton inertial lengths—indicates that current sheets at all heliocentric distances are predominantly kinetic-scale structures whose width is set by the local plasma conditions.

1.3.3.4.2 Current Density and Scale-Dependent Properties

The current density within kinetic-scale current sheets is not independent of their spatial scale. Vasko et al. (2022) found at 1 AU that the current density increases systematically for thinner structures, following $J_0 \approx 6 \text{ nA/m}^2 \cdot (\lambda/100 \text{ km})^{-0.56}$, but does not statistically exceed a critical value J_A corresponding to an ion-electron drift at the local Alfvén speed. In normalized units, this becomes $J_0/J_A \approx 0.17 \cdot (\lambda/\lambda_p)^{-0.51}$. A corresponding power-law correlation was observed near the Sun by Lotekar et al. (2022), who found $J_0 \approx 0.15 \mu\text{A/m}^2 \cdot (\lambda/100 \text{ km})^{-0.76}$ with current densities in the range $0.1\text{--}10 \mu\text{A/m}^2$, and at 5 AU by Vasko et al. (2024), who reported $J_0/J_A \approx 0.14 \cdot (\lambda/\lambda_p)^{-0.66}$ with typical current densities of $0.05\text{--}0.5 \text{ nA/m}^2$.

These current sheets are statistically force-free: the current density is dominated by its magnetic-field-aligned component, consistent with the observation that $|B|$ does not vary substantially across them. The magnetic shear angle is also correlated with spatial scale: Vasko et al. (2022) found $\Delta\theta \approx 19^\circ \cdot (\lambda/\lambda_p)^{0.5}$ at 1 AU, while Vasko et al. (2024) found $\Delta\theta \approx 16.6^\circ \cdot (\lambda/\lambda_p)^{0.34}$ at 5 AU. These scale-dependent correlations—thinner sheets carrying proportionally stronger currents with smaller shear angles—are a natural consequence of the turbulent cascade, in which magnetic field gradients steepen as energy is transferred to smaller scales. The approximate scale-invariance of these relationships across heliocentric distances (from 0.17 AU to 5 AU), together with the matching of magnetic field rotation and compressibility between current sheets and the ambient turbulence, provides strong evidence that the majority of kinetic-scale current sheets are produced by the turbulent cascade.

The observation that current density does not exceed the Alfvén current density J_A is physically significant but not yet fully understood. From the standpoint of reconnection, Vasko et al. (2021) showed that essentially all 18,785 kinetic-scale current sheets in their dataset satisfy the necessary condition for reconnection not to be suppressed by diamag-

netic drift of the X-line. This condition, $\Delta\beta \lesssim 2(L/\lambda_p) \tan(\Delta\theta/2)$, is automatically met due to the geometry of the current sheets as dictated by the turbulent cascade, rather than being a coincidence of local plasma parameters. The same conclusion was reached near the Sun (Lotekar et al., 2022) and at 5 AU (Vasko et al., 2024).

1.3.3.5 Alfvénicity, Walén Relation and Propagation Direction

The relationship between velocity and magnetic field variations across current sheets—their degree of Alfvénicity—has been a central and persistently debated topic, bearing directly on the classification of discontinuities as RDs or TDs and on their dynamical role in the solar wind.

The pioneering observation by Neugebauer (1985), using IMP 8 and Voyager 2 data, revealed that velocity and magnetic field jumps ($\Delta\mathbf{v}$ and $\Delta\mathbf{B}/\sqrt{\rho}$) across tangential discontinuities (a large change in magnetic field strength) are closely aligned—either parallel or antiparallel—in the sense associated with outward-propagating Alfvén waves. This alignment was found to be independent of solar wind stream structure and heliocentric distance between 1 and 2.2 AU. The result was unexpected for structures classified as TDs, and several explanations were proposed, including interplanetary turbulence, large-amplitude Alfvénic fluctuations propagating independently on both sides of the discontinuity, and surface waves on TDs.

Neugebauer et al. (1986) confirmed using Helios data that this alignment is already well established inside 0.4 AU, suggesting it is not a product of in situ evolution but may instead reflect a selection effect: TDs for which $\Delta\mathbf{v}$ and $\Delta\mathbf{B}$ are not aligned are destroyed by the Kelvin–Helmholtz instability, so that only Alfvénically aligned TDs survive. The observed decrease in the total number of discontinuities with increasing heliocentric distance may be associated with the growth of this instability as the Alfvén speed declines.

An earlier comprehensive study by Neugebauer et al. (1984), using ISEE 3 data, showed that the relative directions of velocity and field changes across all three discontinuity types (RD, TD, and the intermediate “either” category, ED) are consistent with outward propagation. The magnitude of the velocity change at RDs was found to be systematically smaller than the MHD prediction — a discrepancy only partially reduced by using a two-

stream proton fit — foreshadowing the broader $R < 1$ puzzle discussed below. Further, the plasma jump conditions at EDs showed closer resemblance to RDs than to TDs.

Quantitative assessment of Alfvénicity relies on the Walén relation, which states that the velocity jump across an RD should equal the corresponding Alfvén velocity jump. Two complementary approaches have been developed (see the bottom panels of Figure 1.9). The first evaluates the Walén relation as a jump condition by comparing velocity and Alfvén velocity changes between two carefully chosen measurement times on opposite sides of the discontinuity. The second checks the level of Alfvénicity continuously for all measurements between those two points: plasma velocity components, after transformation into the de Hoffmann–Teller (HT) frame, are plotted against the corresponding Alfvén velocity components, and the slope of the regression line, W_{sl} , serves as the quality index, with $W_{sl} = \pm 1$ indicating perfect Alfvénic agreement.

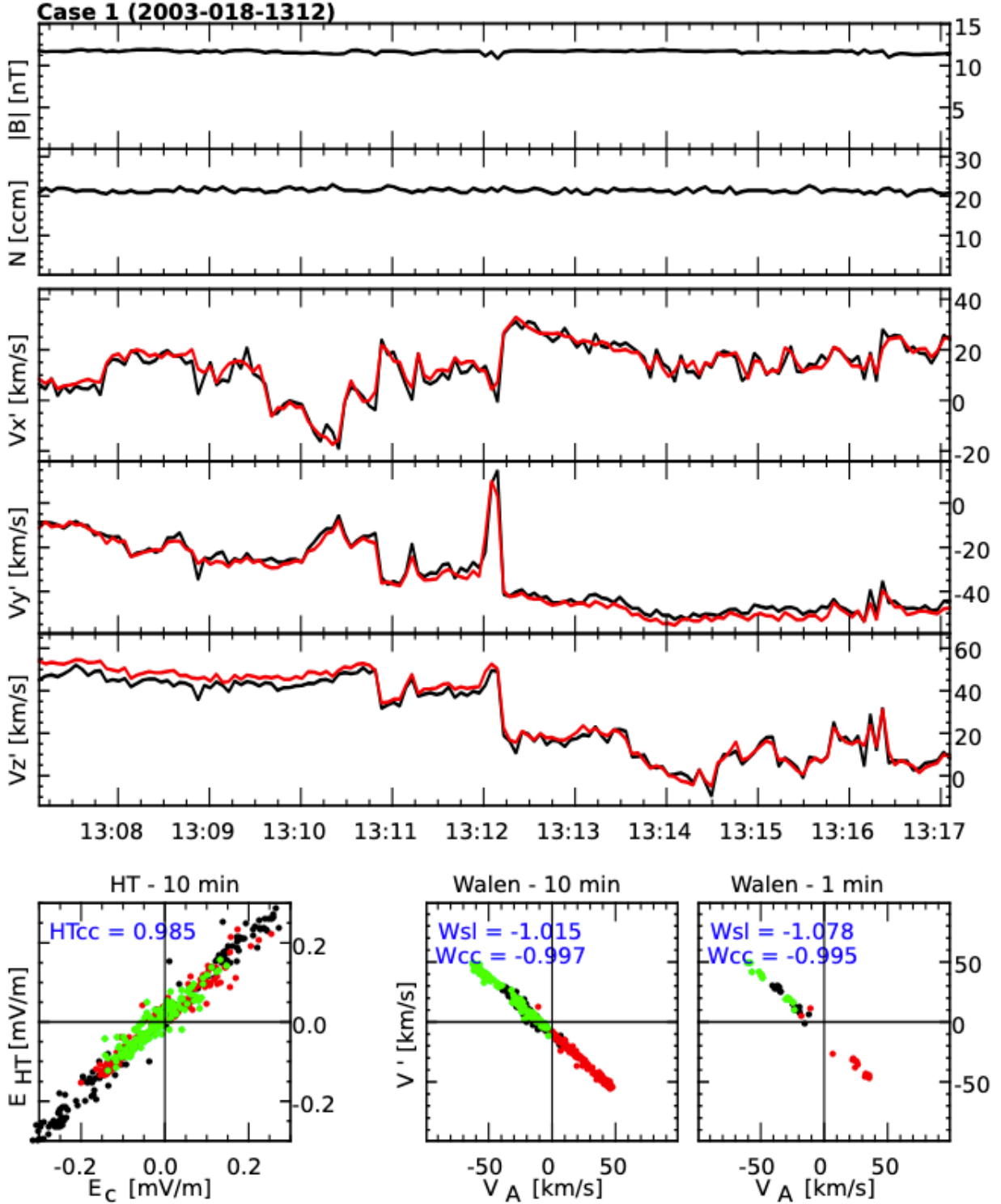


Figure 1.9: Overview plots for DD crossings. For each case, the five panels at the top show the magnetic field magnitude, the plasma density, followed by a comparison between the three components of $\mathbf{v}' = (\mathbf{v} - \mathbf{V}_{HT})$ (in black) and (in red) the three components of $-\mathbf{V}_A$ or $\mathbf{V}_A$ (depending on the sign of the Walén slope), all from Cluster C1, with the DD at the center of the time series. The panels along the bottom show the HT scatterplot for the 10 min interval, and the Walén scatterplots for the full 10 min and for the 1 min interval centered on the DD. In these scatterplots the vector components are distinguished by their color (black for x, red for y, and green for z).

Neugebauer (2006) reported that the magnitude ratio $R = |\Delta \mathbf{v}| / |\Delta \mathbf{v}_A|$ from the jump approach is commonly around 0.6—systematically less than unity. Paschmann et al. (2013), using Cluster data, performed a comprehensive Walén analysis on 188 directional discontinuities and found that a substantial fraction (77 out of 127 with a good de Hoffmann–Teller frame) exhibited plasma flow speeds exceeding 80% of the Alfvén speed, with 33 cases exceeding 90%. Their analysis also established that the degree of Alfvénicity of the coherent current sheets is nearly the same as that of the fluctuations in which they are embedded, suggesting that whatever process causes deviations from ideal Alfvénicity operates equally on both. This result places current sheets on a continuum with the ambient Alfvénic turbulence rather than as dynamically distinct structures.

A critical complication in using the Walén test for RD/TD classification was identified by Madar et al. (2024), who analyzed over 140,000 directional discontinuities between 0.06 and 1.01 AU using Parker Solar Probe and Solar Orbiter data. They showed that Alfvén waves propagating along the surface of TDs can produce positive Walén test results, mimicking RD signatures. To disentangle the two populations, they examined the velocity in the HT frame: for surface waves on TDs, the residual velocity $(\mathbf{V} - \mathbf{V}_{\text{HT}})$ lies close to the discontinuity plane, whereas for genuine RDs it is quasi-perpendicular to the surface. A scatter plot of B_n/B_{max} against $(\mathbf{V} - \mathbf{V}_{\text{HT}}) \cdot \hat{n} / |\mathbf{V} - \mathbf{V}_{\text{HT}}|$ revealed two clearly distinct populations, confirming that many apparent RD candidates are in fact TDs with surface Alfvén waves. After this reclassification, they found that most discontinuities with small normal magnetic field components are TDs, regardless of the jump in field magnitude.

The systematic shortfall $R < 1$ has remained a longstanding puzzle. As noted by Paschmann et al. (2013), this deficiency mirrors the behavior of Alfvénic fluctuations more broadly: the Alfvén ratio $r_A = \delta v^2 / \delta v_A^2$ is known to decrease systematically with heliocentric distance, reaching approximately 0.5 at 1 AU (Belcher & Davis Jr., 1971; Borovsky, 2012).

Refined scalar measures for evaluating Alfvénicity have been developed to disentangle directional and magnitude deviations. Sonnerup et al. (2018) introduced a quality index Q that incorporates both the angular deviation and the magnitude ratio between $\Delta \mathbf{v}$ and $\Delta \mathbf{v}_A$, with $Q = \pm 1$ indicating perfect agreement. Paschmann et al. (2020) systematically

compared the jump-based index Q with the regression slope W_{sl} across nearly 1,000 magnetopause crossings, finding that a substantially higher threshold is needed for $|Q|$ than for $|W_{sl}|$ to yield comparable numbers of RD candidates, and that the events selected by the two methods are not identical. They concluded that a complete evaluation of Alfvénicity requires two scalar quality measures: the magnitude ratio $R = |\Delta \mathbf{v}| / |\Delta \mathbf{v}_A|$ and the angle Θ between $\Delta \mathbf{v}$ and $\Delta \mathbf{v}_A$ (Paschmann et al., 2018).

1.3.3.6 Additional Statistical Properties

This subsection briefly summarizes several additional properties of solar wind current sheets that, while not the primary focus of this thesis, form an important part of the broader observational picture and provide useful context for interpreting the current sheet population.

1.3.3.6.1 Orientation

The orientation of current sheet normals relative to the local magnetic field depends on both the type of discontinuity and heliocentric distance. In the inner heliosphere, Mariani et al. (1973) analyzed Pioneer 8 data (10 s cadence) and found that TD normals are predominantly perpendicular to the local Parker Archimedean spiral field, consistent with TDs separating adjacent flux tubes. Söding et al. (2001) corroborated this and highlighted a contrasting behavior for rotational discontinuities (RDs): inner heliospheric RD normals are primarily parallel to the mean field, $\mathbf{B}_0$ (i.e., the normal-to-field angle $\gamma \approx 0^\circ$). This aligns with Alfvén waves propagating along the field, although obliquely propagating RDs are also present. Conversely, in the middle heliosphere (10–40 AU), the distribution of γ becomes nearly uniform across all directions, with a notable depletion of RDs propagating parallel to $\mathbf{B}_0$. To explain this radial evolution, Söding et al. (2001) suggested that field-aligned RDs are unstable over large spatial and temporal scales so the effects of this instability are absent in the inner heliosphere (0.3–2.3 AU) but become pronounced at greater distances.

1.3.3.6.2 Plasma Beta Dependence

The properties of current sheets depend on the local plasma β . Shaikh et al. (2026), using interplanetary coronal mass ejections as a natural laboratory spanning a broad range of beta ($10^{-2} \lesssim \beta_e \lesssim 10$, $10^{-3} \lesssim \beta_p \lesssim 10$), showed that both the shear angle $\Delta\theta$ and the normalized thickness λ/λ_p of current sheets depend on electron and proton beta. They argued that the beta dependence of the shear angle is an intrinsic feature of solar wind

turbulence arising from the natural correlation between turbulence intensity and plasma beta. According to recent theory, current sheets formed in turbulence are disrupted by the electron tearing instability once their thickness falls below a critical scale, mediating the transition from the inertial to the kinetic cascade (Mallet et al., 2017). Shaikh et al. (2026) demonstrated that normalizing current sheet thickness by this critical scale eliminates the beta dependence across the entire measured range.

1.3.3.6.3 Bifurcated Current Sheets and Reconnection Exhausts

A distinctive subclass of solar wind current sheets exhibits bifurcated structure—a double-step magnetic field rotation rather than as a single monotonic rotation (Gosling, 2012; Neugebauer & Giacalone, 2010). As reviewed by Gosling (2012), these bifurcated current sheets are the observational signature of magnetic reconnection in the solar wind. When reconnection occurs, the reconnecting current sheet splits into a pair of back-to-back rotational discontinuities that bound a wedge of accelerated plasma—the reconnection exhaust. The exhaust plasma flows at roughly the local Alfvén speed, with correlated changes in $\mathbf{V}$ and $\mathbf{B}$ at one boundary and anti-correlated changes at the other, reflecting the oppositely propagating Alfvénic disturbances generated by the reconnection process.

The observational picture of reconnection in the solar wind has developed rapidly since the first unambiguous identification of reconnection exhausts by Gosling et al. (2005). Using Wind 3-second data, Gosling (2012) reported typical occurrence rates of 40–80 exhausts per month at 1 AU near solar minimum, with most events having temporal widths of tens of seconds (local widths of order 10^4 km). Reconnection occurs most frequently at current sheets with field shear angles below 90° —simply because such current sheets are the dominant type in the solar wind—and has been observed at shear angles as small as 11° (Gosling & Szabo, 2008). The narrowest exhaust identified had a local width of $\sim 10^3$ km ($\sim 18 \lambda_i$), and current sheets thinner than $\sim 3 \lambda_i$ were absent from the dataset, suggesting that such ultrathin structures are quickly disrupted by reconnection.

Multi-spacecraft observations have revealed that reconnection in large-scale current sheets typically occurs in a quasi-stationary fashion at a single dominant, extended X-line. The most extensive event documented involved five spacecraft and demonstrated continuous reconnection persisting for over 5 hours along an X-line extending at least 4.26×10^6 km (Gosling, 2012). Exhaust boundaries are roughly planar on large scales, though finer-

scale corrugations are sometimes observed. The occurrence of reconnection depends on a combination of magnetic shear angle and the plasma β difference across the current sheet: for low β , reconnection occurs at essentially all shear angles, whereas for high β it is restricted to large shear angles—consistent with the theoretical prediction that diamagnetic drift of the X-line suppresses reconnection at low-shear, high- β current sheets.

Gosling & Szabo (2008), examining an interval containing 11 reconnection exhausts and 27 thin current sheets within a magnetic cloud and its trailing high-speed stream, found that at least three of the thin sheets also exhibited bifurcated structure, indicating that they had been disrupted by reconnection. The relative absence of ultrathin current sheets was interpreted as evidence that such structures are rapidly disrupted once they form. More recently, Yoon et al. (2021) showed through particle-in-cell simulations that bifurcated current sheets can also arise naturally from the collisionless equilibration of a disequilibrium current sheet, through transitions among single-particle orbit classes, without requiring active reconnection. This suggests that not all observed bifurcated structures necessarily indicate ongoing or recent reconnection, and that collisionless relaxation may be an additional pathway to bifurcation.

It should be noted that the reconnection exhausts described above are observed at relatively large-scale current sheets resolvable with 3-second plasma cadence ($\gtrsim 10^3$ km). Whether reconnection at kinetic-scale current sheets—the focus of this thesis—produces qualitatively similar or distinct signatures remains an active area of investigation, as discussed in the context of reconnection onset conditions earlier in this chapter.

1.3.3.6.4 Contribution to the Magnetic Fluctuation Spectrum

Current sheets contribute significantly to the power of magnetic field fluctuations in the solar wind. Borovsky (2010), analyzing 8.5 years of ACE magnetometer data, constructed an artificial time series preserving only the timing and amplitudes of strong (large-rotation-angle) discontinuities. The power spectrum of this discontinuity series follows a power law in the inertial subrange with spectral index near the Kolmogorov $-5/3$ value, and accounts for approximately half of the total spectral power of the solar wind magnetic field over this range. This result warns that the measured spectral properties of solar wind turbulence are heavily influenced by the discrete contribution of current sheets, complicating the interpretation of spectral indices.

Li et al. (2011) provided complementary evidence from three years of Ulysses data in which over 28,000 current sheets were identified. They showed that during the longest current-sheet-free intervals, the magnetic field power spectra are consistently described by the Iroshnikov–Kraichnan $k^{-3/2}$ scaling, whereas during the most current-sheet-abundant intervals, the spectra exhibit Kolmogorov $k^{-5/3}$ scaling. This finding implies that the commonly observed Kolmogorov scaling in the solar wind may be a consequence of the ubiquitous presence of current sheets rather than an intrinsic property of the underlying turbulent cascade, and that a proper analysis of solar wind power spectra must account for the contribution of intermittent structures.

1.3.3.6.5 Other Plasma Jump Conditions

Beyond the magnetic field signatures discussed above, the behavior of plasma parameters across current sheets provides additional constraints on their nature and on the validity of the RD/TD classification.

Neugebauer et al. (1984) conducted a comprehensive examination of plasma jump conditions across 221 discontinuities using ISEE 3 magnetic field and proton data. They found that the first and second adiabatic invariants ($T_{p\perp}/B$ and $T_{p\parallel}B^2/n^2$) are approximately conserved across RDs but not across TDs, confirming that the MVA-based classification into these two types captures a genuine physical distinction. The product of plasma density and the anisotropy factor, ρA , tends to be conserved across all three discontinuity types (RDs, TDs, and EDs)—a result expected for RDs but not required by MHD theory for TDs. The helium abundance n_α/n_p is generally conserved across RDs but can change substantially across TDs; however, a broad tail in the n_α/n_p distribution for RDs indicates that the helium abundance does change at a small fraction of them.

The multi-species dynamics at RDs proved particularly revealing. Neugebauer et al. (1984) showed that the primary and secondary proton beams flow through RDs in opposite directions with oppositely directed velocity changes, while alpha particles interact much more weakly—with velocity changes clustered near zero and no preferred direction. They proposed a simple model in which the RD moves through the primary proton fluid at slightly less than the local Alfvén speed; because the alpha particles drift relative to the primary protons at approximately this same speed, they effectively co-move with the RD and do not cross it. Under these conditions, the jump conditions for alphas resemble

those across a contact discontinuity, explaining how the helium abundance can change even across a genuine RD. When this multi-stream model was used to recalculate the Walén ratio R_{VB} , it increased from 0.59 ± 0.03 (single-stream proton moments) to 0.74 ± 0.02 , and further inclusion of alpha particle anisotropy and estimated electron contributions raised it to 0.77 ± 0.03 —diminishing but not eliminating the longstanding $R_{VB} < 1$ discrepancy.

The properties of the magnetically ambiguous EDs were found to resemble those of RDs much more closely than those of TDs across essentially all parameters: adiabatic invariants, density conservation, helium abundance, Walén ratio, and mean solar wind speed. This led Neugebauer et al. (1984) to conclude that the ED population consists predominantly of obliquely propagating RDs with small but finite B_n , rather than TDs with coincidentally small $\Delta|B|$.

1.3.4 Summary and Open Questions

The body of work reviewed in this chapter establishes a rich but incomplete picture of solar wind current sheets. Their basic phenomenology is well characterized: the magnetic field rotates through a shear angle with only weak magnitude variation; the thickness of kinetic-scale current sheets is typically a few proton inertial lengths regardless of heliocentric distance; current density scales inversely with thickness in a manner consistent with the turbulent cascade; and occurrence rates decrease with radial distance from the Sun, though the precise scaling depends sensitively on identification criteria and corrections for solar wind speed and current sheet orientation. The majority of these structures are statistically force-free, satisfy the necessary conditions for magnetic reconnection onset, and share the Alfvénic character of the ambient turbulence in which they are embedded.

Despite this progress, several important questions remain open and motivate the investigations presented in subsequent chapters of this dissertation.

Unified method across scales and distances. Previous studies have typically examined either large-scale discontinuities or kinetic-scale current sheets, often with different identification methods, instrumental cadences, and spacecraft datasets. As a result, a

coherent picture of how the current sheet population evolves across spatial scales and heliocentric distances has not yet emerged. Developing a detection framework capable of capturing current sheets over a broad range of scales — from the kinetic regime to the MHD regime — and applying it consistently across multiple radial distances would therefore be highly valuable.

Separation of temporal variability from radial evolution. A persistent difficulty in interpreting radial trends is the contamination by temporal variability. Occurrence rates fluctuate substantially on timescales from hours to solar rotations, and single-spacecraft surveys at different heliocentric distances inevitably sample different solar wind conditions at different times. Multi-spacecraft observations and extended orbital coverage offer opportunities to separate genuine spatial evolution from temporal modulation, but this separation has rarely been achieved systematically for the kinetic-scale population.

Multi-scale nature, distinct sub-populations, and their origins. Current sheets span a vast range of spatial scales, and it is plausible that structures at different scales originate from different physical mechanisms — for example, coronal flux-tube boundaries, nonlinear Alfvén wave steepening, or turbulence-driven intermittency. Furthermore, these distinct populations may follow different evolutionary paths as they propagate outward with the solar wind. Observational evidence already hints at such differentiation: the RD-to-TD ratio declines steeply inside 0.5 AU, pointing to fundamentally different generation mechanisms and lifetimes for the two classes. Yet at kinetic scales, the classical TD/RD distinction becomes blurred, as individual structures frequently exhibit signatures of both types simultaneously. Identifying physically meaningful sub-populations within the current sheet ensemble, characterizing their properties, and tracking their evolution with heliocentric distance remains an important challenge.

Interaction with energetic particles. The spatial scales of kinetic-scale current sheets — comparable to the gyro-radii of energetic particles in the keV to MeV range — place them in a regime where adiabatic particle motion breaks down. The cumulative effect of encounters with such structures on pitch-angle scattering, cross-field transport, and particle energization is not yet quantitatively understood from an observational standpoint.

Establishing the statistical framework of current sheet properties is a necessary prerequisite for addressing these transport questions, which will be taken up in later chapters.

These questions collectively define the motivation for the analyses presented in the following chapters: Chapter 2 and Chapter 3 develop and apply a consistent methodology for identifying and characterizing current sheets from 0.17 to 5 AU, while Chapter 4 and Chapter 5 examine how the observed current sheet properties shape energetic particle scattering and transport.

1.4 Energetic Particle Interaction With Solar Wind Current Sheets

The transport of energetic particles through the heliosphere is governed not only by the large-scale structure of the interplanetary magnetic field, but also by the small-scale, intermittent structures embedded within it (Engelbrecht et al., 2022; Ewart et al., 2025; Oughton & Engelbrecht, 2021; van den Berg et al., 2020). Chief among these are current sheets—thin layers of intense current and rapid magnetic field rotation that occupy a small fraction of the heliospheric volume yet exert a disproportionate influence on particle dynamics. This section reviews the theoretical and observational foundations necessary to understand how energetic particles interact with these structures, with particular focus on the mechanisms by which current sheets scatter particles in pitch angle and modulate their transport through the heliosphere.

We begin with the heliospheric context: the sources and classification of solar energetic particles, and the observational phenomena—reservoir effects and dropout events—that reveal the dual role of current sheets as both barriers and facilitators of transport. We then describe the standard transport frameworks within which pitch-angle scattering is parameterized, and discuss how solar wind turbulence intermittency motivates going beyond classical wave-based scattering theories. The core of the section develops the quasi-adiabatic theory of charged particle dynamics near magnetic field reversals, tracing how the adiabatic invariant breaks down at separatrix crossings through geometrical and dynamical jumps—a scattering mechanism qualitatively distinct from, and potentially more efficient than, wave–particle resonance (Artemyev et al., 2013b). The section closes with a summary

of the key results and a discussion of the open questions that motivate the quantitative program developed in subsequent chapters.

1.4.1 Energetic Particles in the Heliosphere

1.4.1.1 Sources of Energetic Particles

The heliosphere hosts several distinct populations of energetic particles spanning a vast range of energies and origins (Simnett, 2017). *Galactic cosmic rays* (GCRs) are high-energy particles originating from outside the solar system—primarily accelerated by supernova shocks—that propagate inward through the heliosphere and are modulated by the solar wind and heliospheric magnetic field (Moraal, 2013; Prantzos, 2012). *Anomalous cosmic rays* (ACRs) represent a population of singly charged ions that originate as interstellar neutral atoms, become ionized upon entering the heliosphere (forming pickup ions), and are subsequently accelerated to energies of tens of MeV at the heliospheric termination shock (Giacalone et al., 2022). *Solar energetic particles* (SEPs), the population most relevant to this thesis, are accelerated at or near the Sun during transient eruptive events and span energies from suprathermal (a few keV) to relativistic ($\sim$ few GeV) (Anastasiadis et al., 2019; Desai & Giacalone, 2016; Klein & Dalla, 2017; Reames, 2013).

Unlike the quasi-steady GCR background, SEP events are episodic and highly variable. Intensities can increase by several orders of magnitude within minutes and exhibit dramatic event-to-event variations in spectral shape, heavy-ion composition, charge states, and spatial distribution (Anastasiadis et al., 2019). This variability reflects both the diverse acceleration mechanisms at the Sun and the complex transport processes that particles undergo as they propagate through the structured, turbulent interplanetary medium (Klein & Dalla, 2017).

1.4.1.2 Two Classes of Solar Energetic Particle Events

SEP events are broadly classified into two categories based on their acceleration mechanism and observational characteristics (Desai & Giacalone, 2016; Reames, 2013; Vlahos et al., 2019):

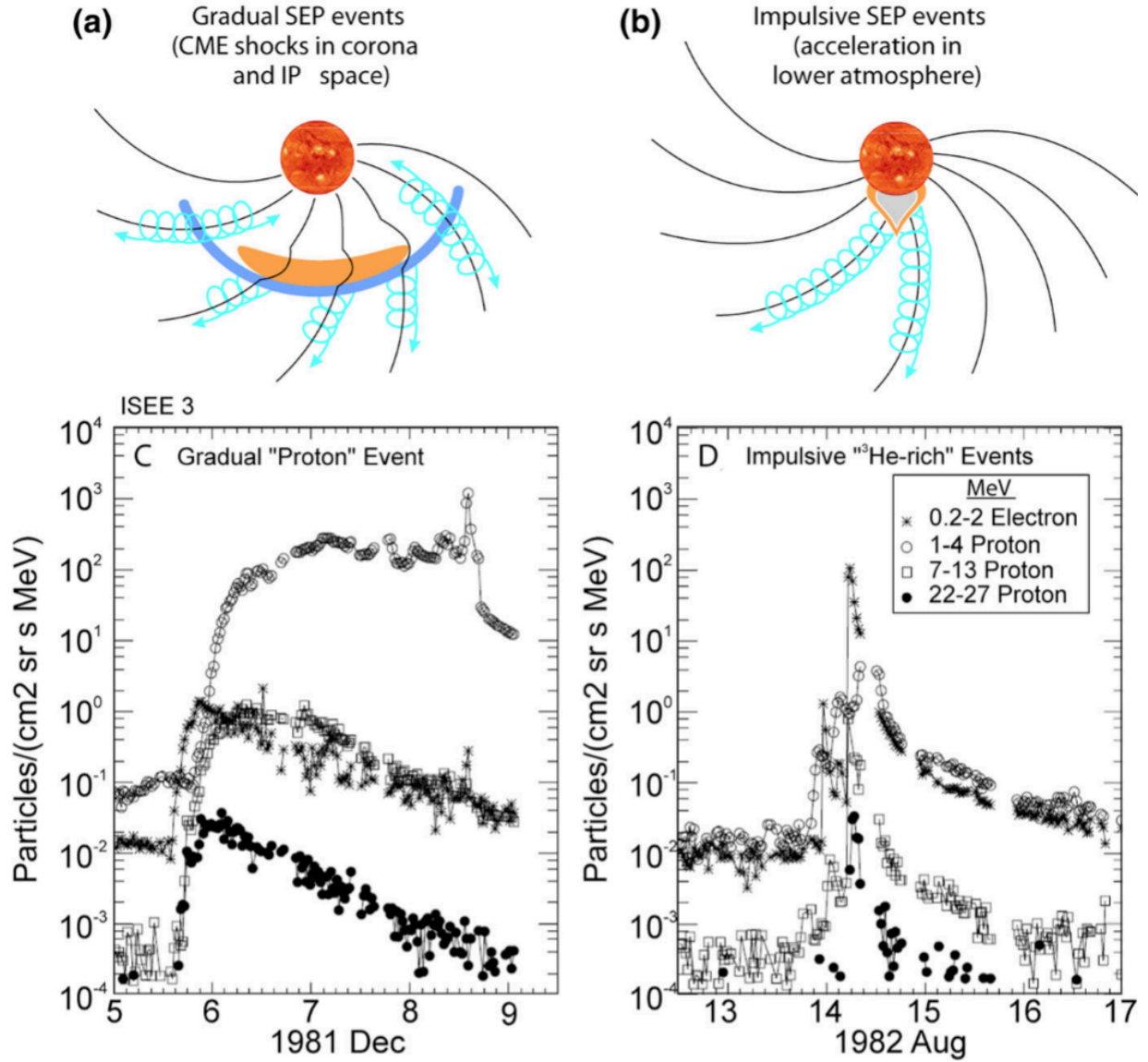


Figure 1.10: The two-class picture for SEP events (Desai & Giacalone, 2016).

Impulsive SEP events are produced by magnetic reconnection-driven processes during solar flares. In the standard picture, reconnection in the solar corona—occurring along open magnetic field lines—accelerates particles through stochastic processes related to turbulence and fragmented current sheets in the reconnection region (Vlahos et al., 2019). Impulsive events are typically short-lived (minutes to hours) and are characterized by several distinctive compositional signatures: large enhancements of $^3\text{He}/^4\text{He}$ (by factors up to ~ 1000 relative to solar wind values), elevated heavy-ion ratios such as Fe/O, high charge states indicating source temperatures of $\sim 3 \times 10^7$ K, and relatively high electron-

to-proton ratios (Reames, 2013). Because the accelerated particles are injected onto a narrow range of magnetic flux tubes rooted in the compact flare site, impulsive events are observed only by spacecraft that are magnetically well-connected to the source—typically spanning only a few tens of degrees in solar longitude.

Gradual SEP events are driven by shock waves propagating through the corona and interplanetary space, typically associated with fast coronal mass ejections (CMEs) (Lee et al., 2012). The CME-driven shock provides a spatially extended acceleration region that can fill a broad range of magnetic field lines as it expands outward, beginning when the shock reaches approximately 2 solar radii (Desai & Giacalone, 2016). Particles are accelerated through diffusive shock acceleration (DSA), in which ions are scattered back and forth across the shock front by self-generated Alfvén waves amplified by the streaming accelerated protons themselves (Klein & Dalla, 2017). Gradual events typically last for several days, are proton-dominant, and exhibit elemental abundances similar to the solar corona and charge states corresponding to source temperatures of $\sim 3 \times 10^6$ K. These events produce by far the highest SEP intensities observed near Earth and represent the primary source of radiation hazard to astronauts, spacecraft electronics, and passengers on high-altitude polar flight routes (Anastasiadis et al., 2019).

While this two-class paradigm provides a useful organizational framework, it is important to note that the boundary between the two classes is not always sharp (Klein & Trotter, 2001). Many large gradual events show elevated ^3He and Fe/O ratios at high energies, suggesting that residual suprathermal ions from previous impulsive events can serve as a seed population for subsequent shock acceleration (Desai & Giacalone, 2016). Furthermore, recent multi-spacecraft observations from widely distributed vantage points (STEREO, ACE, SOHO, and more recently Parker Solar Probe and Solar Orbiter) have revealed that SEPs can fill remarkably broad regions of the heliosphere—often extending over more than 180° in longitude—challenging simple models of localized injection and raising fundamental questions about the relative roles of extended shock geometry, coronal transport, and interplanetary cross-field diffusion in distributing particles throughout the inner heliosphere (Anastasiadis et al., 2019; Klein & Dalla, 2017).

1.4.1.3 Reservoir and Dropout Phenomena

Two contrasting observational signatures of SEP transport provide particularly compelling evidence for the role of magnetic structure in controlling particle propagation:

The **reservoir effect** (or invariant spectra) is frequently observed during the decay phase of large gradual SEP events. Particle intensities measured by widely separated spacecraft (sometimes at different heliocentric distances and heliolatitudes) become nearly equal and exhibit similar temporal decay profiles, with energy spectra that maintain an invariant shape as overall intensities decrease (Desai & Giacalone, 2016; Reames, 2013). The three-dimensional character of the reservoir, revealed by high-heliolatitude observations from the Ulysses mission (Dalla et al., 2003), favors explanations involving substantial cross-field transport that distributes particles throughout a large volume of the inner heliosphere, rather than simple trapping behind an expanding magnetic-bottle-like structure. The velocity-dependent migration of particles through the tangled interplanetary field—potentially mediated by interactions with current sheets and other coherent structures—is a natural candidate mechanism for establishing such spatially uniform distributions.

In stark contrast, **dropout events** are characterized by abrupt, sharp variations (depletions) in energetic particle intensity, often observed during impulsive SEP events (Mazur et al., 2000; Tessein et al., 2015). Spacecraft crossing from one magnetic flux tube into an adjacent one observe sudden drops (or increases) in particle count rates, with the intensity boundaries occurring on spatial scales comparable to particle gyro-radii (Neugebauer & Giacalone, 2015). This behavior indicates that particles are effectively confined within distinct flux tubes with minimal lateral transport. The sharp boundaries between particle-filled and particle-empty flux tubes are frequently identified with tangential discontinuities in the solar wind magnetic field, which act as barriers to cross-field propagation because no magnetic field component threads through their surface ($B_n = 0$).

Together, these observations highlight a fundamental duality: current sheets can both *impede* particle transport (when acting as flux tube boundaries at tangential discontinuities) and *facilitate* it (through scattering that decouples particles from their field lines at rotational discontinuities). The relative importance of these two effects depends on the internal structure of the current sheets and the particle energy—a theme developed quantitatively in this thesis.

1.4.1.4 Turbulence Transport Frameworks

The large-scale transport of energetic particles through the heliosphere is governed by a competition between parallel streaming along magnetic field lines, scattering by magnetic fluctuations, adiabatic focusing in the diverging interplanetary magnetic field, convection with the solar wind, and gradient-curvature drifts (Dalla et al., 2013). The foundational framework is the Parker transport equation (Parker, 1965b), which describes the evolution of the nearly isotropic part of the particle distribution using a diffusive approximation (justified when the particle scattering time is short compared to the timescale of interest):

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial x_i} \left[\kappa_{ij} \frac{\partial f}{\partial x_j} \right] - U_i \frac{\partial f}{\partial x_i} - V_{d,i} \frac{\partial f}{\partial x_i} + \frac{1}{3} \frac{\partial U_i}{\partial x_i} \frac{\partial f}{\partial \ln p} + \text{Sources} - \text{Losses},$$

where f is the omnidirectional distribution function, κ_{ij} is the symmetric part of the diffusion tensor, U_i is the solar wind velocity, $V_{d,i}$ is the gradient-curvature drift velocity, and p is the particle momentum. The drift velocity can be formally derived from the guiding center approximation averaged over a nearly isotropic distribution, and can be included as the antisymmetric part of the diffusion tensor. The diffusion tensor can be decomposed into components parallel ($\kappa_{\parallel}$) and perpendicular ($\kappa_{\perp}$) to the mean magnetic field: $\kappa_{ij} = \kappa_{\perp} \delta_{ij} + (\kappa_{\parallel} - \kappa_{\perp}) B_i B_j / B^2$.

The parallel diffusion coefficient is related to the pitch-angle diffusion coefficient $D_{\mu\mu}$ through the quasi-linear theory (QLT) framework (Jokipii, 1966):

$$\kappa_{\parallel} = \frac{v^2}{8} \int_{-1}^1 \frac{(1 - \mu^2)^2}{D_{\mu\mu}(\mu)} d\mu,$$

where $\mu = \cos \alpha$ is the pitch-angle cosine and v is the particle speed. This relation makes $D_{\mu\mu}$ the central microphysical quantity controlling parallel transport: all the physics of particle–field interaction is encoded in this single function of pitch angle.

When significant anisotropy is present—as during the early phases of SEP events, near interplanetary shocks, or when focusing effects are important—the focused transport equation (Earl, 1976; Roelof, 1969) retains the explicit pitch-angle dependence:

$$\frac{\partial f}{\partial t} + \mu v \frac{\partial f}{\partial z} + \frac{v}{2L}(1 - \mu^2) \frac{\partial f}{\partial \mu} = \frac{\partial}{\partial \mu} \left(D_{\mu\mu} \frac{\partial f}{\partial \mu} \right),$$

where $L = -B(dB/dz)^{-1}$ is the focusing length characterizing the divergence of the magnetic field.

In both frameworks, the pitch-angle diffusion coefficient $D_{\mu\mu}$ is the quantity most directly shaped by magnetic turbulence. Its value is governed by several key turbulence parameters — spatial inhomogeneity, fluctuation level ($\delta B/B_0$), spectral index, and wave-vector anisotropy (Chandran, 2000; Pucci et al., 2016). Solar wind turbulence spans an enormous range of scales, from the large-scale coherence length (~ 0.01 AU) down to kinetic dissipation scales near the thermal ion gyroradius (~ 100 km). The most relevant portion for energetic particle transport is the inertial range: for a 5 nT background field, this range corresponds to proton gyro-radii from roughly 1 keV to 1 GeV, a window encompassing nearly all SEPs.

Classical scattering theory evaluates $D_{\mu\mu}$ by modeling the turbulence as a superposition of random, low-amplitude, phase-uncorrelated waves with power-law spectra, in which particles scatter via cyclotron resonance with fluctuations at scales matching their gyroradius (Jokipii, 1966; 1967). Many numerical models adopt the same idealization, constructing magnetic fluctuations — such as the slab component $\delta \mathbf{B}^s$ and two-dimensional component $\delta \mathbf{B}^{2D}$ (Equation 1) — without accounting for the intermittent, structured nature of real solar wind turbulence. This approach has well-known limitations: it fails to scatter particles through $\mu = 0$ (the 90° pitch-angle problem) and produces mean free paths that disagree with observational inferences.

$$\begin{aligned} \delta \mathbf{B}^s &= \sum_{n=1}^{N_m} A_n [\cos \alpha_n (\cos \phi_n \hat{x} + \sin \phi_n \hat{y}) + i \sin \alpha_n (-\sin \phi_n \hat{x} + \cos \phi_n \hat{y})] \times \exp(ik_n z + i\beta_n) \\ \delta \mathbf{B}^{2D} &= \sum_{n=1}^{N_m} A_n i (-\sin \phi_n \hat{x} + \cos \phi_n \hat{y}) \times \exp[ik_n (\cos \phi_n x + \sin \phi_n y) + i\beta_n] \end{aligned} \quad (1)$$

1.4.1.5 New model of particle transport in reversing magnetic fields

The standard paradigm of cosmic ray transport assumes small-amplitude fluctuations ($\delta B/B_0 \ll 1$) about a strong mean magnetic field and relies on quasi-linear theory to relate

the pitch-angle diffusion rate to the magnetic power spectrum. Kempfski et al. (2023) and Lemoine (2023) challenge this paradigm by studying particle transport in the opposite asymptotic limit: large-amplitude MHD turbulence with $\delta B/B_0 \gg 1$, where the turbulence stretches and folds field lines into highly intermittent structures with ubiquitous small-scale reversals.

The magnetic field geometry is characterized by the field-line curvature $K_{\parallel} \equiv |\hat{\mathbf{b}} \cdot \nabla \hat{\mathbf{b}}|$ and the inverse perpendicular reversal scale $K_{\perp} \equiv |\hat{\mathbf{b}} \times (\hat{\mathbf{b}} \times \nabla \ln B)|$. The PDFs of these quantities reveal that $K_{\perp}^{-1} \ll l_B$, where l_B is the parallel coherence length, indicating that the field is organized into *fold*-like structures: elongated regions of roughly straight field connected by tight bends where $K_{\parallel} \sim K_{\perp}$. Regions of large curvature have systematically weaker fields, with $\langle B(K_{\parallel}) \rangle \propto K_{\parallel}^{-1/2}$ —consistent with approximate constancy of the magnetic tension $\mathbf{B} \cdot \nabla \mathbf{B}$. This anti-correlation between curvature and field strength appears to be a robust feature of MHD turbulence: similar curvature statistics have been measured in diverse simulation settings (Schekochihin et al., 2001; Yang et al., 2019; Yuen & Lazarian, 2020), and confirmed *in situ* in the Earth’s magnetosheath (Bandyopadhyay et al., 2020; S. Y. Huang et al., 2020) and solar wind (Hu et al., 2025).

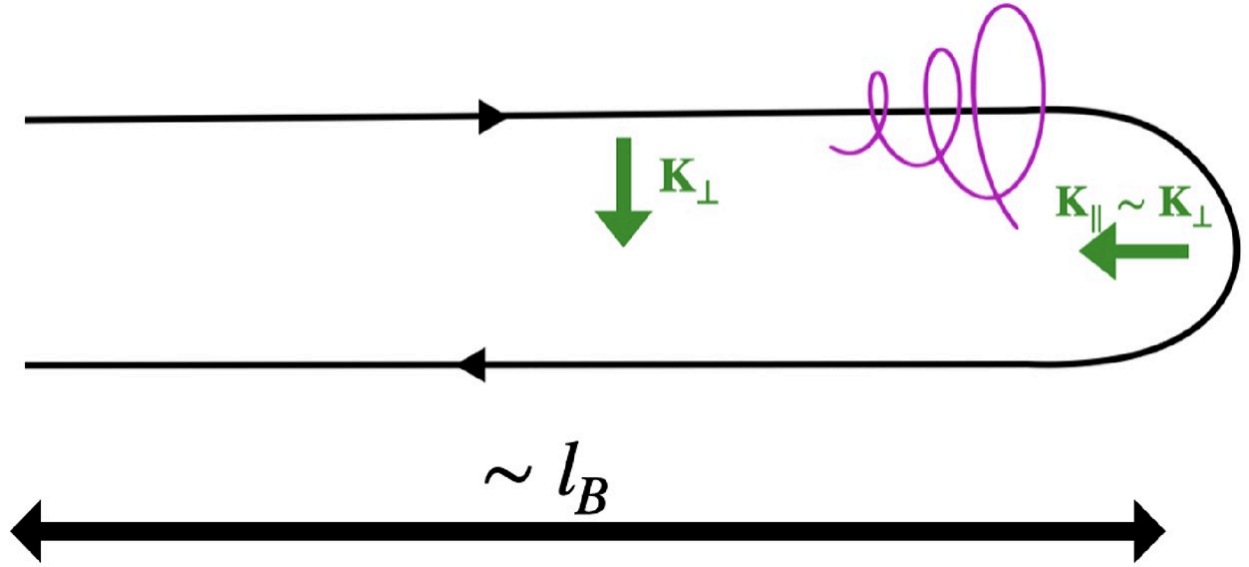


Figure 1.11: Schematic of particle transport in a magnetic fold. The fold has parallel coherence length $\sim l_B$ and perpendicular reversal scale $K_{\perp}^{-1} \ll l_B$. Along the straight segments $K_{\parallel} \ll K_{\perp}$; at the bend, $K_{\parallel} \sim K_{\perp}$. The magenta trajectory illustrates a particle whose gyroradius grows as B weakens near the bend (Kempfski et al., 2023).

The transport of a particle through such a fold depends on its gyroradius relative to the perpendicular reversal scale. A particle with $r_{L0} \gg K_{\perp}^{-1}$ is not magnetized on the scale of the fold: it samples many field reversals within a single gyro-orbit, so the opposing field contributions partially cancel and the effective magnetic force on the particle is suppressed. Such high-energy particles are largely insensitive to the fold structure. For $r_{L0} < K_{\perp}^{-1}$, the particle can gyrate around the field line along the straight segments where $K_{\parallel} \ll K_{\perp}$, but as it approaches the bend the weakening field increases its gyroradius and decreases its gyrofrequency. Three outcomes then result: (i) if $\Omega \gg K_{\parallel}c$ at the bend, the particle adiabatically follows the reversing field, undergoing effective spatial ‘scattering’ through the field-line random walk without pitch-angle change—a mechanism with no analogue in strong guide-field transport, where a particle perfectly following a field line does not random walk; (ii) if $\Omega \sim K_{\parallel}c$, the particle experiences ‘resonant curvature’—order-unity pitch-angle scattering analogous to the $\kappa_l r_g \gtrsim 1$ criterion of Lemoine (2023); (iii) if $\Omega \ll K_{\parallel}c$, the particle demagnetizes and drifts out of the fold via ∇B drift before completing the reversal. The resulting heuristic scattering frequency is

$$\nu(r_{L0}) \sim \frac{c}{l_B} \int^{K_{\max}} P(K_{\perp}) dK_{\perp}, \quad (2)$$

where $l_B = \int K_{\parallel}^{-1} P(K_{\parallel}) dK_{\parallel}$ is the characteristic parallel coherence length. The upper limit $K_{\max}(r_{L0})$ encodes the magnetization condition at the bend: $K_{\max} r_{L0} = f_r \langle B(K_{\parallel} = K_{\max}) \rangle / B_{\text{rms}}$, with $f_r \sim \mathcal{O}(1)$. Using $\langle B \rangle \propto K_{\parallel}^{-1/2}$ yields $K_{\max} \propto r_{L0}^{-2/3}$, so that lower-energy particles can traverse a larger fraction of folds and are better confined.

The perpendicular reversal scale $K_{\perp}$ plays a role with no analogue in quasi-linear theory. In effect, it controls the fraction of the fold population that contributes to the effective scattering frequency. It does not directly scatter particles, but sets the curvature of the bend at the end of each fold, thereby determining whether particles satisfy the resonant-curvature condition or follow the reversal adiabatically.

1.4.1.6 Pitch-Angle Scattering by Current Sheets

Solar wind turbulence is highly intermittent: magnetic energy and current density concentrate into thin, intense current sheets that occupy a small fraction of the volume yet account for a disproportionate share of the dissipation (Borovsky, 2010). The scattering

produced by these coherent structures is fundamentally different from wave–particle resonance. When a particle’s gyroradius is comparable to the sheet thickness ($\rho \sim L$), the interaction involves separatrix crossings in phase space and the associated destruction of the quasi-adiabatic invariant I_z (discussed in detail in the following sections). The resulting pitch-angle changes are large— $\Delta\alpha \sim \mathcal{O}(1)$ in the case of geometrical chaotization—and occur on timescales comparable to a single gyroperiod, far faster than the gradual diffusion assumed in quasi-linear theory. Because kinetic-scale current sheets are abundant in the solar wind (Vasko et al., 2022; Vasquez et al., 2007), and their thickness overlaps with the gyro-radii of energetic particles at typical field strengths, a propagating particle will encounter many such structures en route from the Sun to Earth. The cumulative pitch-angle scattering from these encounters contributes to an effective $D_{\mu\mu}$ through a mechanism that is qualitatively distinct from—and potentially more efficient than—classical wave–particle resonance.

A complementary perspective comes from Lemoine (2023), who studied the role of sharp magnetic field bends—characterized by the local curvature $\kappa \equiv B^{-1} | \mathbf{b} \times (\mathbf{b} \cdot \nabla) \mathbf{B} |$ —in a simulation of incompressible MHD without a mean field. When a particle crosses a region where the curvature radius shrinks below its gyroradius ($\kappa_l r_g \gtrsim 1$ on scale $l \sim r_g$), the magnetic moment changes by order unity—precisely the ‘resonant curvature’ mechanism identified by Kempfski et al. (2023). In a root-mean-square sense, such regions should not exist: the characteristic curvature scales as $\kappa_l \sim (l/\ell_c)^{-1/3} \ell_c^{-1}$ following the Goldreich–Sridhar cascade, giving $\kappa_l r_g \ll 1$ for $r_g \ll \ell_c$. The key insight is that the non-Gaussian, power-law tails of the curvature p.d.f. (see Figure 1.12) guarantee that sufficiently many scattering-strength bends exist on all scales $l < \ell_c$ to sustain transport. This yields a mean free path

$$\lambda_s \equiv \frac{l}{\int_1^\infty p_{\hat{\kappa}_l l}(x) dx} \Big|_{l \sim \bar{r}_g} \sim \ell_c^{0.7} \bar{r}_g^{0.3}, \quad (3)$$

a scaling distinct from quasi-linear predictions that arises entirely from the intermittent structure of the turbulence. Particle tracking confirms that magnetic moment diffusion proceeds through localized, violent interactions rather than continuous weak scattering:

the p.d.f. of the normalized magnetic moment $\widehat{M}(t) \equiv M(t)/M(0)$ broadens via power-law tails rather than Gaussian spreading, producing non-Brownian transport on scales $\lesssim \ell_c$.

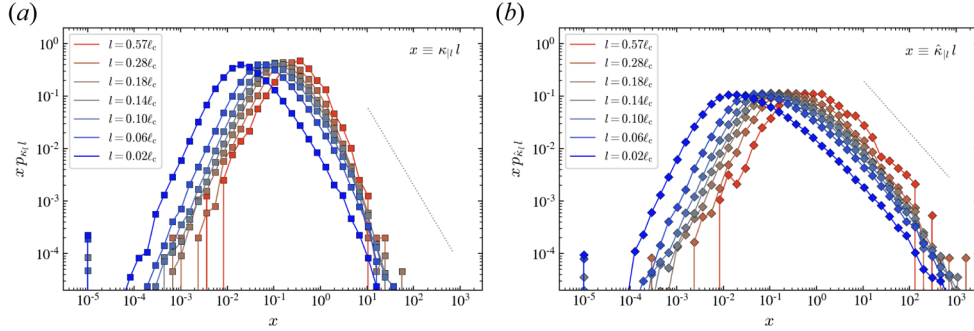


Figure 1.12: Lemoine (2023) (a) Statistics of the curvature κ_l coarse grained on scale l (multiplied by l), as measured through direct sampling in the JHU-MHD simulation, for various coarse-graining scales, as indicated. Note that the y -axis shows $x p_{\kappa_l l}(x)$ where $x \equiv \kappa_l l$. The dotted line shows a scaling $p_{\kappa_l l}(x) \propto x^{-2.5}$, for reference. (b) Same, for the normalized curvature $\hat{\kappa}_l l$. The dotted line shows a scaling $p_{\hat{\kappa}_l l}(x) \propto x^{-2.0}$, for reference. See text for details.

1.4.1.7 Perpendicular Transport

While parallel transport is relatively well understood, perpendicular (cross-field) transport remains more elusive due to its nonlinear and non-resonant nature (Costa Jr. et al., 2013; Shalchi, 2021). In the classical picture, cross-field diffusion arises from two mechanisms: the random walk of magnetic field lines, which carries particles across the mean field, and the decorrelation of particles from their original field lines through scattering. The perpendicular diffusion coefficient $\kappa_{\perp}$ is typically assumed to be a small fraction of $\kappa_{\parallel}$ (Giocalone & Jokipii, 1999), but this assumption is challenged on two fronts: observations—such as the reservoir effect and the broad longitudinal spread of SEP events—demand significant cross-field transport, and recent simulations show that $\kappa_{\perp}$ can be substantial and strongly dependent on particle energy and turbulence structure (Dundovic et al., 2020). The dimensionality of the turbulence also matters (Giocalone & Jokipii, 1994): in models with at least one ignorable spatial coordinate (e.g., slab geometry), cross-field diffusion is artificially suppressed, omitting essential physics.

The intermittent-scattering framework introduces cross-field mechanisms that go beyond the classical field-line random walk, which dominates cross-field motion in the quasi-linear regime with a strong guide field. In the fold-propagation model of Kempfski et al. (2023), particles that demagnetize at fold bends ($\Omega \ll K_{\parallel} c$) drift out via ∇B drift, producing

cross-field displacements of order $K_{\perp}^{-1}$. For particles that do traverse the bend, the field-line random walk provides rigidity-independent perpendicular diffusion with $\kappa_B \sim c l_B$. The relative importance of these two channels depends on the particle energy through the hierarchy of $K_{\max}(r_{L0})$ and K_{peak} , the latter defined as the $K_{\perp}$ at which $K_{\perp}P(K_{\perp})$ is maximal. For large r_{L0} with $K_{\max} \gg K_{\text{peak}}$, resonant-curvature scattering dominates and cross-field transport is rigidity-dependent; for small r_{L0} with $K_{\max} \ll K_{\text{peak}}$, the field-line random walk takes over and the perpendicular diffusion becomes independent of particle energy. The transition between these regimes, and the interplay of the two contributions, may produce a $\kappa_{\perp}$ with complex energy dependence qualitatively different from the standard $\kappa_{\perp} \propto \kappa_{\parallel}$ scaling.

Lemoine (2023) emphasizes a complementary mechanism rooted in the same intermittent structures. The systematic anti-correlation between field-line curvature and magnetic field strength means that non-adiabatic, magnetic-moment-violating interactions occur precisely where the field is weak and inhomogeneous on gyroradius scales. During such interactions, the particle is effectively demagnetized and can jump to a neighboring field line. Even outside these non-adiabatic regions, strong curvature and ∇B gradients drive perpendicular drifts with velocities $v_D \sim v r_g / (3L)$ for modes on scale $L > r_g$. While the displacement per interaction is small ($r_g \ll L$), the cumulative effect over many scattering events provides an additional source of cross-field transport.

Current sheets deserve particular attention in this context, as they concentrate several of these mechanisms simultaneously. For an idealized one-dimensional force-free current sheet (e.g., a force-free Harris sheet), however, there is no ∇B drift and no field-line random walk—the classical perpendicular transport channels are absent. Nonetheless, the field becomes highly inhomogeneous on scales comparable to or smaller than the gyroradius: particles become unmagnetized and escape their initial field lines. This current-sheet-driven mechanism may constitute a genuinely non-diffusive contribution to cross-field transport.

A quantitative theory of perpendicular transport in the intermittent-scattering regime remains to be developed. The joint statistics of the curvature κ and the mirror term $m \equiv B^{-1} \hat{\mathbf{b}} \cdot (\hat{\mathbf{b}} \cdot \nabla) B$ along field lines are likely correlated—both are large at current sheets—yet

their combined influence on perpendicular decorrelation has not been quantified (Lemoine, 2023). The topology of high-curvature regions, whether they form isolated patches or connected networks, will determine how efficiently successive scattering events translate into macroscopic cross-field diffusion. Furthermore, the non-Brownian character of parallel transport on scales $\lesssim \ell_c$ identified by Lemoine (2023) suggests that perpendicular transport may also exhibit anomalous features on sub-coherence-length scales.

1.4.1.8 Evidence for Current Sheet Modulation of SEP Intensity

Direct observational evidence for the influence of current sheets on SEP transport comes from studies at both large and small scales. At the large scale of the heliospheric current sheet (HCS), Liou & Wu (2024) performed a superposed epoch analysis of 319 HCS crossings observed by the Wind spacecraft, finding a systematic drop in 2–10 MeV/nucleon helium flux at the HCS that was strongest at low energies and diminished at higher energies. They identified 15 individual SEP flux dropout events coinciding with HCS crossings, all originating from western-hemisphere sources at longitudes far from the crossing location—indicating that the HCS severed the magnetic connection between the particle source and the observer. The energy dependence of the dropout fraction is consistent with more effective scattering or blocking of lower-energy particles whose gyro-radii are comparable to the current sheet thickness. The transport and drift effects of the HCS have also been characterized through simulation. Battarbee et al. (2017) integrated fully three-dimensional proton trajectories near an analytically defined flat HCS in the 1–800 MeV range, finding that gradient and curvature drifts along the sheet can carry protons to longitudes far from their injection site—producing multi-component intensity profiles that could be misinterpreted as evidence for multiple injection events—and confirming that the HCS acts as an effective barrier to cross-hemisphere transport. Extending this work to a more realistic geometry, Battarbee et al. (2018) modeled SEP propagation near a wavy HCS whose position was constrained by fits to magnetic source surface maps. They found that the waviness of the sheet introduces longitudinally periodic enhancements in particle fluence and enables efficient longitudinal transport along the sheet, with the magnitude and spatial distribution of these effects depending sensitively on the IMF polarity configuration (A+ vs. A−) and the HCS tilt angle.

At smaller scales, Tessein et al. (2015) analyzed over 12 years of ACE observations and found a strong statistical correlation between coherent structures—identified using the partial variance of increments (PVI) method, which detects current sheets and sharp magnetic field gradients—and energetic particle intensity variations in the 0.047–4.78 MeV range. Local PVI maxima frequently coincided with regions of rising or falling particle intensity, suggesting that magnetic discontinuities act as local barriers or modulators of transport. This correlation persisted after removing shock-associated intervals, confirming that the effect is intrinsic to the current sheets rather than a byproduct of shock-related enhancements.

1.4.1.9 Non-Diffusive Transport Effects

Beyond classical diffusion, SEP observations and measurements near interplanetary shocks frequently reveal anomalous transport behavior, characterized by subdiffusive or superdiffusive scaling of mean-square displacement with time, $\langle \Delta x^2(t) \rangle \propto t^\alpha$ with $\alpha \neq 1$ (Zimbardo et al., 2006; 2015). These deviations from normal diffusion ($\alpha = 1$) are attributed to the intermittent, structured nature of solar wind turbulence and are better captured by generalized frameworks such as fractional diffusion models (del-Castillo-Negrete et al., 2005) or Lévy statistics (Zaburdaev et al., 2015).

The interactions with current sheets have implications that extend beyond modifications to the diffusion coefficients. When pitch-angle changes are dominated by rare but intense jumps rather than continuous weak scattering, the statistical assumptions underlying the diffusion approximation can break down (Lemoine, 2023). Current sheets can induce non-Markovian memory effects (Zimbardo & Perri, 2020): correlations in the spatial arrangement and properties of current sheets mean that scattering at one structure influences both the likelihood and character of scattering at the next. The intermittent, clustered distribution of current sheets in the solar wind naturally generates the heavy-tailed step-size distributions that underlie anomalous transport in both regimes—subdiffusive ($\alpha < 1$) when sheets trap particles, and superdiffusive ($\alpha > 1$) when intense encounters produce large pitch-angle jumps and correspondingly large spatial displacements.

1.4.2 Quasi-Adiabatic Dynamics of Charged Particles and Its Destruction in Current Sheets

1.4.2.1 Adiabatic Motion and Its Breakdown

A charged particle moving in a magnetic field that varies slowly in space and time possesses an approximate conservation law. The particle gyrates around the magnetic field line with a characteristic frequency—the cyclotron frequency $\Omega_c = qB/mc$ —and a characteristic radius—the gyroradius (or Larmor radius) $\rho = v_\perp/\Omega_c$, where $v_\perp$ is the velocity component perpendicular to the magnetic field. If the magnetic field changes only gradually over the spatial scale of the gyro-orbit, the particle’s magnetic moment

$$\mu = \frac{mv_\perp^2}{2B}$$

is approximately conserved. This quantity, the first adiabatic invariant, is the foundation of guiding-center theory (Northrop, 1963), in which the rapid gyromotion is averaged out and the particle is described by the drift of its guiding center along and across the magnetic field. The conservation of μ underlies many fundamental phenomena in space physics, including magnetic mirroring, radiation belt trapping, and the confinement of particles in magnetic bottles.

The key assumption of guiding-center theory is that the magnetic field varies on spatial scales much larger than the particle’s gyroradius: $L_B \gg \rho$, where L_B is the characteristic length scale of the field gradient. When a particle encounters a magnetic structure whose thickness λ is comparable to or smaller than its gyroradius—that is, when $\lambda \sim \rho$ —this assumption breaks down. The particle can no longer complete a full gyration within a region of approximately uniform field. The magnetic moment ceases to be conserved, and the guiding-center description fails (Escande & Sattin, 2021). This is precisely the situation that arises when energetic particles interact with kinetic-scale current sheets in the solar wind, where the structure thickness is on the order of the ion inertial length d_i or a few ion gyro-radii.

A different theoretical framework is needed to describe particle dynamics in this regime. Rather than averaging over the gyromotion (as in guiding-center theory), one must identify the appropriate fast periodic motion for the specific field geometry and construct the corresponding adiabatic invariant. This is the domain of the quasi-adiabatic theory (Whipple et al., 1986; Zelenyi et al., 2013), which we now describe.

1.4.2.2 Adiabatic Invariants in Slow–Fast Hamiltonian Systems

The mathematical foundation for understanding particle motion in current sheets lies in the general theory of slow–fast Hamiltonian systems and their adiabatic invariants. We follow the review by Neishtadt (2019), which provides a comprehensive treatment of the mechanisms by which adiabatic invariance can be destroyed.

Consider a Hamiltonian system in which the variables naturally separate into fast and slow degrees of freedom. The fast variables (p, q) oscillate rapidly, while the slow variables (y, x) evolve on a much longer timescale, controlled by a small parameter $\varepsilon \ll 1$. The equations of motion take the form

$$\dot{p} = -\frac{\partial E}{\partial q}, \quad \dot{q} = \frac{\partial E}{\partial p}, \quad \dot{y} = -\varepsilon \frac{\partial E}{\partial x}, \quad \dot{x} = \varepsilon \frac{\partial E}{\partial y}.$$

For frozen values of the slow variables, the fast system describes periodic motion. One can then introduce *action-angle variables* (I, φ) for this periodic motion, where the action

$$I = \frac{1}{2\pi} \oint p \, dq$$

is the area enclosed by the orbit in the fast phase plane, divided by 2π . Averaging the equations of motion over the fast phase φ yields the *adiabatic approximation*:

$$I = \text{const}, \quad \dot{y} = -\varepsilon \frac{\partial H_0}{\partial x}, \quad \dot{x} = \varepsilon \frac{\partial H_0}{\partial y},$$

where $H_0(I, y, x)$ is the Hamiltonian expressed in terms of the action and slow variables. The action I is an *adiabatic invariant*: it is conserved with accuracy $O(\varepsilon)$ over time intervals of order $1/\varepsilon$.

Under favorable conditions, conservation can be much better than this. When the system has two degrees of freedom (one fast, one slow) and the phase portrait of the fast system is everywhere filled by closed trajectories (no separatrices), Arnold showed that invariant tori of the exact system fill the energy surface up to a residue of small measure, and the adiabatic invariant is conserved perpetually: $|I(t) - I(0)| = O(\varepsilon)$ for all time (Arnol'd,

1963). This result has direct physical consequences: it implies, for example, that charged particles can be confined indefinitely in axisymmetric magnetic traps.

1.4.2.3 Separatrix Crossing and Destruction of Adiabatic Invariance

The situation changes fundamentally when the phase portrait of the fast system contains a *separatrix*—a trajectory that separates topologically distinct regions of phase space. Figure 1.13 illustrates the generic structure: a saddle point C in the fast phase plane generates separatrices l_1 and l_2 that divide the portrait into three domains G_1 , G_2 , and G_3 , each corresponding to a different type of periodic motion. For example, G_1 and G_2 might correspond to oscillations in two separate potential wells, while G_3 corresponds to oscillations spanning both wells.

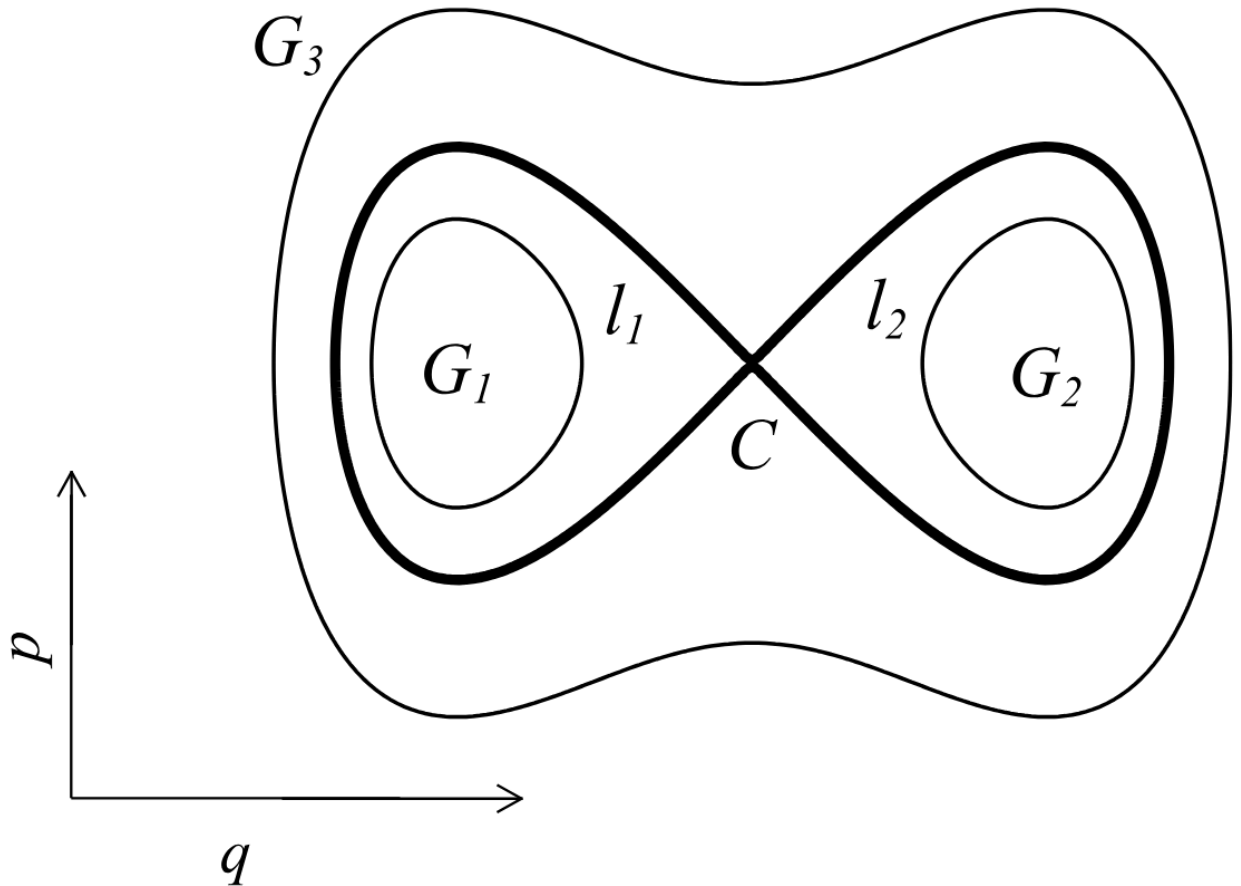


Figure 1.13: Phase portrait of the fast system (Neishtadt, 2019).

As the slow variables evolve, the phase portrait of the fast system changes shape, and a trajectory that was initially in one domain can be driven toward the separatrix and cross

into another domain. This crossing has profound consequences for the adiabatic invariant (Tennyson et al., 1986). There are two distinct contributions to its change:

1. **Geometrical jump.** When a trajectory crosses from, say, domain G_3 (the large outer domain) to G_1 (one of the inner domains), the area enclosed by the orbit changes discontinuously—from $S_3 = S_1 + S_2$ to S_1 . This purely geometric change ΔI^{geom} is independent of ε and is determined entirely by the relative areas of the separatrix loops at the moment of crossing.
2. **Dynamical jump.** In addition to the geometric change, the logarithmic divergence of the oscillation period T near the separatrix produces a correction $\Delta I^{\text{dyn}} \sim \varepsilon \ln \varepsilon$. The precise value of this correction depends sensitively on the phase of the fast motion at the moment of crossing, parameterized by a variable ξ . This quantity varies rapidly ($\sim 1/\kappa$ times faster than the slow evolution) and can be treated as a uniformly distributed random variable $\xi \in (0, 1)$.

Because the dynamical jump depends sensitively on initial conditions ($O(\varepsilon)$ changes in initial data produce $O(1)$ relative changes in the jump), the outcome of separatrix crossing is effectively probabilistic. The probability of entering domain G_i after crossing from G_3 is $P_i = \Theta_i / \Theta_3$, where $\Theta_i = \{S_i, h_c\}$ is the Poisson bracket of the area of domain G_i with the value of the Hamiltonian E (energy) at the saddle point C . The accumulation of geometrical and dynamical jumps over multiple separatrix crossings destroys the adiabatic invariance and leads to chaotic dynamics.

1.4.2.4 Application to Current Sheets: the Quasi-Adiabatic Invariant

The motion of charged ions in a magnetic field reversal—the configuration of a current sheet—provides the most physically important application of this theory. Consider a current sheet with a reversing field $B_x(z) = B_0(z/L)$ (where L is the half-thickness), a small normal component B_z , and an optional guide field B_y . In normalized variables, the Hamiltonian for ion motion takes the form (Artemyev et al., 2013a)

$$H = \frac{1}{2}p_z^2 + \frac{1}{2}(p_x - sz)^2 + \frac{1}{2}\left(\kappa x - \frac{1}{2}z^2\right)^2,$$

where the two key dimensionless parameters are

$$\kappa = \frac{B_z}{B_0} \sqrt{\frac{L}{\rho_0}}, \quad s = \frac{B_y}{B_0} \sqrt{\frac{L}{\rho_0}},$$

with $\rho_0 = \sqrt{2\hbar mc}/(qB_0)$ being the characteristic Larmor radius for a particle of energy h . The parameter κ controls the separation of timescales: $\kappa \ll 1$ means the coordinate z (normal to the current sheet) oscillates rapidly while κx (along the reversing field direction) evolves slowly. For typical ions in the Earth's magnetotail current sheet, $\kappa \in [0.01, 0.1]$; for energetic ions interacting with solar wind current sheets, κ can range from ~ 0.01 to ~ 0.3 depending on the particle energy and current sheet thickness.

The structure of the fast motion in the (z, p_z) plane depends on the instantaneous values of the slow variables $(\kappa x, p_x)$. The effective potential energy is

$$U(z) = \frac{1}{2}(p_x - sz)^2 + \frac{1}{2}\left(\kappa x - \frac{1}{2}z^2\right)^2.$$

This potential can have either two local minima separated by a maximum (forming two potential wells) or a single minimum (a single well), depending on $(\kappa x, p_x)$. The two-well structure corresponds physically to the particle oscillating about a magnetic field line on one side of the current sheet, while the single-well structure corresponds to the particle oscillating across the neutral plane $z = 0$, executing figure-eight-like orbits that span both sides of the sheet.

Since the fast motion is periodic at any frozen value of the slow variables, one can define the quasi-adiabatic invariant

$$I_z = \frac{1}{2\pi} \oint p_z dz,$$

which is the action variable of the fast oscillation. This quantity was first introduced in this context by Büchner and Zelenyi (1986, 1989) and plays a role analogous to the magnetic moment μ of guiding-center theory, but is appropriate for the regime $\lambda \sim \rho$ where guiding-center theory fails. In the adiabatic approximation, $I_z = \text{const}$, and the equation $I_z(\kappa x, p_x) = \text{const}$ (at fixed energy $H = h$) determines closed trajectories in the

slow-variable plane $(\kappa x, p_x)$. These trajectories describe the slow drift of the particle as it oscillates back and forth in z .

The boundary between regions of the slow-variable plane corresponding to the two types of fast motion (two wells vs. one well) is called the *uncertainty curve*. When a particle's trajectory in the $(\kappa x, p_x)$ plane reaches the uncertainty curve, the corresponding trajectory in the (z, p_z) plane crosses the separatrix—the particle switches from oscillating on one side of the current sheet to oscillating across both sides, or vice versa. It is at these crossings that the quasi-adiabatic invariant I_z undergoes jumps and the adiabatic approximation breaks down.

1.4.2.5 Symmetric Current Sheets: Slow Diffusion

In the simplest and most-studied case—a current sheet without a guide field ($s = 0$)—the phase portrait in the (z, p_z) plane is symmetric about $z = 0$. The two separatrix loops enclose equal areas, $S_l = S_r$, and they grow and shrink in synchrony as the slow variables evolve. As a consequence, the geometrical jumps at two successive separatrix crossings (one entering the single-well regime, one returning to a double-well regime) exactly cancel and do not contribute to stochastization (in other words, geometrical jumps can be absorbed into a factor-of-two renormalization of I_z). Only the dynamical jumps remain, and for the symmetric system these take the well-known form (Büchner & Zelenyi, 1989; Cary et al., 1986)

$$\Delta I_z^{\text{dyn}} = -\frac{2}{\pi} \kappa p_x \ln(2 \sin \pi \xi),$$

where $\xi \in (0, 1)$ is the quasi-random phase variable. Since the average over ξ vanishes— $\langle \Delta I_z^{\text{dyn}} \rangle_\xi = 0$ —there is no directed drift in the invariant space. The destruction of I_z proceeds as a diffusive random walk: each jump has amplitude $\sim \kappa$, jumps occur at intervals $\sim 1/\kappa$ (one period of slow motion), and the variance accumulates as $\langle (\Delta I_z)^2 \rangle \sim \kappa^2 \cdot (\kappa t)$. A substantial (order-unity) change in I_z therefore requires a time $\sim \kappa^{-3}$. For typical magnetotail parameters ($\kappa \sim 0.05$ – 0.1), this corresponds to stochastization timescales of tens of minutes—slow, but physically relevant for the lifetime of thin current sheet configurations.

An important phenomenon in the symmetric system is *resonant interaction*. If the phase accumulated between two successive separatrix crossings satisfies a specific condition ($W =$

π , where W is determined by the integral of the fast frequency Ω_z along the adiabatic trajectory), then the two dynamical jumps can exactly compensate: $\sum \Delta I_z^{\text{dyn}} = 0$. This condition depends on κ but not on the random variable ξ , so it can be simultaneously satisfied for an entire population of particles with the appropriate energy. The resulting coherent particle beams (“beamlets”) have been observed in the Earth’s magnetotail and studied extensively (Büchner & Zelenyi, 1989).

1.4.2.6 Guide Field Effects on the Quasi-Adiabatic Theory

The introduction of a guide field ($B_y \neq 0$, corresponding to $s \neq 0$ in the Hamiltonian) breaks the symmetry of the system and profoundly alters the quasi-adiabatic dynamics. Artemyev et al. (2013a) developed the complete quasi-adiabatic theory for arbitrary values of s , identifying new types of particle trajectories and new mechanisms of invariant destruction that have no counterpart in the symmetric ($s = 0$) case. We summarize the key results here; the reader is referred to that paper for full details.

1.4.2.6.1 Modified phase-space structure

In the symmetric system ($s = 0$), the slow-variable plane ($\kappa x, p_x$) is divided into two domains by the uncertainty curve (a half-circle $(\kappa x)^2 + p_x^2 = 1$, $\kappa x > 0$): a domain (t1) where the particle oscillates in one of two symmetric potential wells (motion along field lines on one side of the sheet), and a domain (t2) where the particle oscillates in a single well spanning both sides of the sheet (motion across the neutral plane). The separatrix in the (z, p_z) plane demarcates these two types of motion, and the uncertainty curve is its projection onto the slow-variable plane.

When $s \neq 0$, the potential $U(z)$ loses its symmetry about $z = 0$: the saddle point shifts to $z = z_c \neq 0$, and the two separatrix loops enclose unequal areas, $S_l \neq S_r$ (see Figure 1.14, schematic). Correspondingly, the slow-variable plane acquires a richer structure. Two new domains appear in addition to (t1) and (t2): domain (t2r), where the particle oscillates in a single well *above* the neutral plane ($z > 0$, both solutions of $U = H$ are positive), and domain (t2l), where it oscillates *below* the neutral plane ($z < 0$). In neither of these new domains does the particle cross $z = 0$. Meanwhile, the (t1) domain—the region with two potential wells and a separatrix—shrinks, and the uncertainty curve contracts from a half-circle to a shorter arc. For $s \geq 1$, the uncertainty curve (and with it the separatrix) vanishes entirely.

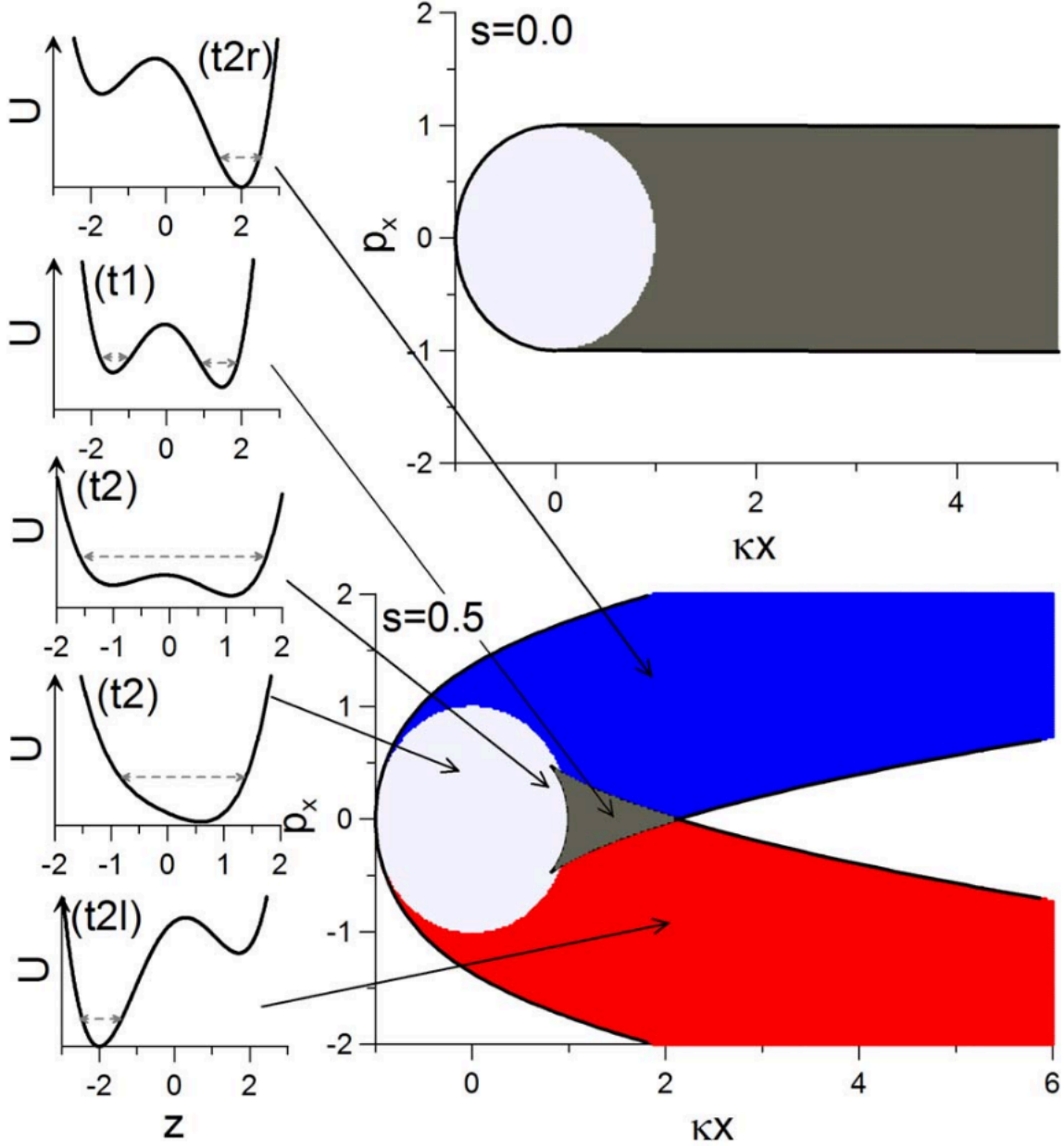


Figure 1.14: The phase plane of slow variables $(\kappa x, p_x)$ is shown for two values of the parameter s . Various colours are used for domains with different types of particle motion. Dotted grey lines show the position of energy level $U = 1/2$ (Artemyev et al., 2013a).

1.4.2.6.2 Trajectory types in the current sheet with B_y

The trajectories of trapped particles in the current sheet without a guide field are simple: the particle oscillates in one potential well, crosses the separatrix into the single well (performing a half-rotation around B_z in the neutral plane), then crosses back into a potential well. In the $(\kappa x, p_x)$ plane this appears as a single closed curve, determined

by $I_z = \text{const}$ with a factor-of-two renormalization at the separatrix to account for the doubling of enclosed area ($S_l = S_r$, so $S = 2S_l$). The motion is simple because the equal areas and synchronous evolution of the two loops ensure that geometrical jumps cancel exactly.

In the system with $B_y \neq 0$, particle trajectories become qualitatively more complex because the areas S_l and S_r are no longer equal and their rates of change Θ_l and Θ_r are no longer identical. Artemyev et al. (2013a) showed that, as a consequence, the trajectory in the $(\kappa x, p_x)$ plane is no longer a single closed curve but a composite object: within each domain, the particle follows a segment of an adiabatic trajectory $I_z(\kappa x, p_x) = \text{const}$, but the value of I_z differs from one domain to the next because of the geometrical jumps ΔI_z^{geom} that occur at each separatrix crossing. The full trajectory is constructed by matching these segments at the uncertainty curve.

A further complication arises from the asynchronous evolution of S_l and S_r . At certain points along the uncertainty curve, one loop area is increasing ($\Theta_l > 0$) while the other is decreasing ($\Theta_r < 0$). At such points, a particle arriving from the (t1) domain has *two possible continuations*: it can cross into the single-well domain (t2), or it can remain in the (t1) domain but switch from the right potential well to the left one (or vice versa). This phenomenon—called *trajectory splitting*—is unique to the asymmetric system. The choice between the two continuations depends on the precise phase of the fast motion at the separatrix crossing, which is effectively random. The probabilities of the two outcomes, P_l , P_r , and $P = 1 - P_l - P_r$ (capture into the left well, right well, or single well respectively), can be calculated analytically from the rates Θ_l and Θ_r at the crossing point (Artemyev et al., 2013a).

Additionally, when $s \neq 0$, a new type of transition appears that has no counterpart in the symmetric system: the particle can switch between the left and right potential wells *without crossing the separatrix at all*. This occurs when one well disappears as the slow variables evolve, the particle is carried smoothly to the position of the other well, and a new well reappears. In the $(\kappa x, p_x)$ plane, this corresponds to the trajectory going around the end of the uncertainty curve rather than crossing it.

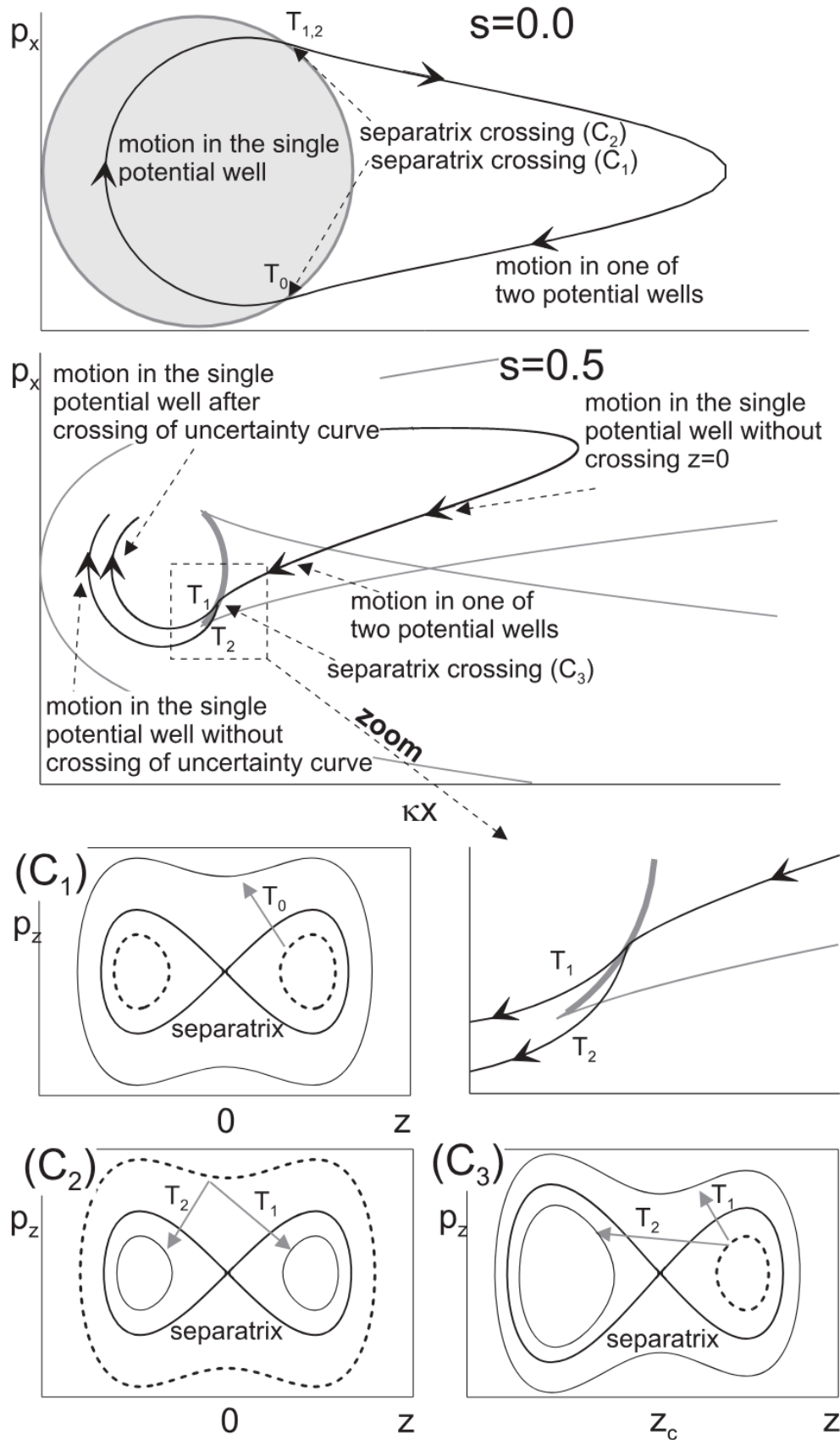


Figure 1.15: Trajectory splitting in the $(\kappa x, p_x)$ plane for $s = 0.5$, showing two possible continuations at the uncertainty curve. Schemes of particle trajectories in systems with $s = 0$ and with $s = 0.5$ are shown in the phase plane $(\kappa x, p_x)$. Fragment of $(\kappa x, p_x)$ plane with trajectory splitting is shown in separated panel. Bottom schemes (C_1 , C_2 , C_3) show particle trajectories before (dotted curves) and after (solid curves)

1.4.2.6.3 Four regimes of particle motion

Artemyev et al. (2013a) identified four distinct regimes of particle dynamics, controlled by the value of s :

1. $0 < s < s_{\text{bif}} \approx 0.25$: Only one type of trajectory exists, analogous to (but more complex than) the trajectories of the symmetric system. Particles cross the uncertainty curve multiple times per period of slow motion, with the number of crossings increasing as $s \rightarrow 0$. At each crossing, geometrical jumps modify I_z , and the trajectory splits into segments matched at the uncertainty curve. Despite this splitting, the total number of crossings is finite and well-prescribed for a given s .
2. $s_{\text{bif}} < s < \bar{s} \approx 0.35$: A second type of trajectory appears in addition to the first. Trajectories of this new type cross the uncertainty curve only twice (once for $p_x > 0$ and once for $p_x < 0$), and the transition between wells occurs without separatrix crossing. Both trajectory types coexist in this range.
3. $\bar{s} < s < 1$: Only the second type of trajectory survives. The rate Θ_r is negative everywhere along the uncertainty curve, meaning that capture into the right well at the separatrix is impossible. All well-switching occurs without separatrix crossing.
4. $s \geq 1$: The separatrix vanishes entirely ($\ell(s) = 0$), and with it all geometrical and dynamical jumps. The quasi-adiabatic invariant is exactly conserved in the adiabatic approximation, and the motion is regular. This critical value corresponds to $B_y > B_0 \sqrt{L/\rho_0}$, the same magnetization criterion derived independently by Galeev and Zelenyi (1978). For $s \gg 1$, the quasi-adiabatic invariant I_z reduces to the ordinary magnetic moment, and the guiding-center theory becomes applicable.

These four regimes are summarized in Table 1 of Artemyev et al. (2013a). The threshold values $s_{\text{bif}} \approx 0.25$ and $\bar{s} \approx 0.35$ are determined by the geometry of the separatrix loop areas and their evolution rates along the uncertainty curve, while $s = 1$ corresponds to the vanishing of the separatrix itself (the uncertainty curve length $\ell(s) = 2 \arctan \sqrt{s^{-4/3} - 1} - s^{1/3} \sqrt{s^{2/3} - s^2}$ reaches zero).

1.4.2.6.4 Importance of geometrical jumps

A key result of Artemyev et al. (2013a) is the demonstration that, for $s > (2/\pi)\kappa \ln 2$ (i.e., $B_y > 0.44B_z$), the geometrical jumps dominate over the dynamical jumps in shaping particle trajectories. In this regime, the adiabatic trajectories in the $(\kappa x, p_x)$ plane are determined primarily by the geometrical jumps—which are of order unity and independent of κ —rather than by the small dynamical jumps $\sim \kappa \ln \kappa$. The dynamical jumps produce only a slow diffusion across these geometrically determined trajectories. For $s < (2/\pi)\kappa \ln 2$, the geometrical jumps become smaller than the dynamical ones and the system behaves effectively like the $s = 0$ case. This separation is the gross features of particle dynamics in a current sheet, with geometrical jumps defining the trajectory structure and dynamical jumps providing the stochastic spreading.

It is important to note that, however, the remaining $z \rightarrow -z$, $p_x \rightarrow -p_x$ symmetry constrains the possible values of I_z to a finite set: the particle’s invariant cycles through a finite number of discrete values, and the trajectories remain closed (though more complex than in the $s = 0$ case). The number of distinct I_z values depends on s and corresponds to the number of uncertainty curve crossings per period of slow motion (which can be counted using the graphical construction in Appendix C of Artemyev et al. (2013a)).

1.4.2.7 Non-adiabatic Effects: Destruction of the Quasi-adiabatic Invariant

The quasi-adiabatic theory developed in the previous subsections treats the invariant I_z as exactly conserved between separatrix crossings and accounts only for the geometrical jumps at crossings. In reality, I_z is only an approximate invariant: it oscillates with amplitude $\sim \kappa$ about its mean value even far from the separatrix, and it undergoes both geometrical and dynamical jumps at each separatrix crossing. A. V. Artemyev et al. (2013) provided a comprehensive analysis of these non-adiabatic effects for the current sheet with sheared magnetic field, deriving analytical expressions for the jumps and quantifying their consequences for particle stochastization. We summarize the key results here.

Understanding the nature, magnitude, and statistics of these jumps is essential for this thesis, because the destruction of I_z is physically equivalent to pitch-angle scattering: I_z determines the particle’s oscillation amplitude in the current sheet, which in turn determines its pitch angle relative to the local magnetic field. A jump in I_z therefore corresponds

directly to a change in pitch angle, and the rate of I_z destruction determines the pitch-angle diffusion rate.

1.4.2.7.1 The improved quasi-adiabatic invariant and its jumps

Far from the separatrix, one can construct an *improved quasi-adiabatic invariant* $J = I_z + \kappa u(z, p_z, \kappa x, p_x)$, where u is a correction function defined at each point of the four-dimensional phase space (except on the separatrix itself). The improved invariant J is conserved with accuracy $\sim \kappa^2$, compared to the accuracy $\sim \kappa$ of the original I_z . This improvement is important because it isolates the true non-adiabatic behavior—the jumps at separatrix crossings $\Delta J = \Delta J^{\text{geom}} + \Delta J^{\text{dyn}}$ —from the oscillatory variations that occur during regular motion. It is through the accumulation of these jumps over multiple separatrix crossings that the quasi-adiabatic invariant is destroyed and particle motion becomes chaotic.

1.4.2.7.2 Nonzero mean dynamical jump and accelerated stochastization

For the symmetric system ($s = 0$), the well-known expression for the dynamical jump is $\Delta J^{\text{dyn}} = -\frac{2}{\pi} \kappa p_x \ln(2 \sin \pi \xi)$. For the asymmetric system ($s \neq 0$), the expressions for ΔJ^{dyn} are considerably more complex. A. V. Artemyev et al. (2013) derived the full expressions for the dynamical jumps using the general formulas of Neishtadt (1987) (the derivation is detailed in Appendix A of that paper). The key difference from the symmetric case is that the expressions involve the *individual* rates of evolution Θ_l and Θ_r (rather than their sum) and the ratio $\tilde{\theta} = \Theta_r/\Theta_l$, which parameterizes the asymmetry. All these parameters are functions of the crossing point along the uncertainty curve, and their asymmetry produces a nonzero $\langle \Delta J^{\text{dyn}} \rangle_\xi$ at each crossing.

The physical consequence of $\langle \Delta J^{\text{dyn}} \rangle_\xi \neq 0$ is profound: it introduces a *directed drift* in the invariant space, superimposed on the diffusive spreading from the random component. The stochastization timescale is then set by the drift rather than the diffusion. Each separatrix crossing changes I_z by $\sim \kappa$ on average (rather than zero on average), and crossings occur at intervals $\sim 1/\kappa$ (one period of slow motion in the $(\kappa x, p_x)$ plane). An order-unity change in I_z therefore requires only $\sim 1/\kappa$ crossings, taking a total time $\sim \kappa^{-2}$ —compared to $\sim \kappa^{-3}$ for the symmetric system where only diffusion operates. For the Earth’s magnetotail with $\kappa \sim 0.05$ – 0.1 , this reduces the stochastization timescale from tens of minutes to a few minutes. It should be noted that the conservation of phase-space volume (Liouville’s theorem) imposes a constraint: the double average $\langle \langle \Delta J^{\text{dyn}} \rangle \rangle_{I_z}$ over the entire particle

population must vanish. That is, while individual values of I_z experience a nonzero mean drift, the net effect over the full distribution is a *redistribution* of invariants without the appearance of net fluxes in phase space. The presence of current sheet boundaries at $|z| = \lambda$ can, however, break this constraint and produce a net drift in the invariant space (Zelenyi et al., 2003).

1.4.2.7.3 Geometrical chaotization: rapid destruction independent of κ

While the nonzero mean dynamical jump accelerates stochastization from κ^{-3} to κ^{-2} , an even faster mechanism exists when the system possesses a fully broken symmetry. As discussed in the quasi-adiabatic theory, the Hamiltonian with $s \neq 0$ retains a residual symmetry: invariance under the combined transformation $z \rightarrow -z, p_x \rightarrow -p_x$. As a result, the net change in I_z after one full period of slow motion is determined by the dynamical jumps alone.

Artemyev et al. (2014) showed that when this residual symmetry is also broken—for example, by a cross-sheet electric field ε that adds a term $\sim -szu_d$ to the Hamiltonian (where $u_d = \varepsilon/\kappa$ is the drift velocity)—the trajectories in the $(\kappa x, p_x)$ plane become asymmetric about $p_x = 0$. The surfaces of constant energy in the four-dimensional phase space that correspond to the two separatrix loops now project onto *different* (shifted) domains in the $(\kappa x, p_x)$ plane. Consequently, the two successive geometrical jumps no longer compensate: $\sum \Delta I_z^{\text{geom}} \neq 0$.

The critical feature of this mechanism is that each geometrical jump ΔI_z^{geom} is of order unity—it equals the difference of the areas of the two separatrix loops, which is a geometric property of the phase portrait and does not depend on κ . This means that even for arbitrarily small κ (arbitrarily thin current sheets or arbitrarily energetic particles), a *single pair* of separatrix crossings produces an $O(1)$ change in I_z . The particle trajectory in the slow-variable plane jumps between widely separated adiabatic curves, and after only a few separatrix crossings the trajectory fills a large domain, with the adiabatic invariant completely destroyed.

Artemyev et al. (2014) termed this mechanism *geometrical chaotization* (an immediate, large-scale redistribution of I_z values) to distinguish it from the much slower *diffusive chaotization* (a gradual Gaussian spreading of I_z distributions with width growing as

$\sqrt{t}$) produced by dynamical jumps. Numerical integration of 10^5 test particle trajectories confirmed that the width of the I_z distribution after ten separatrix crossings is dramatically broader in the fully asymmetric system (3) than in either the symmetric case (1) or the partially symmetric case (2; $s \neq 0$ but no electric field). As shown in Figure 1.16, system (3) has a broad, nearly uniform distribution over a wide range of I_z values (complete invariant destruction) while system (1) peaks narrowly at $I_z/I_{z, \text{init}} = 1$ (slow diffusion) and system (2) splits into a few discrete peaks (the finite number of possible I_z values due to geometrical jumps with compensating sums).

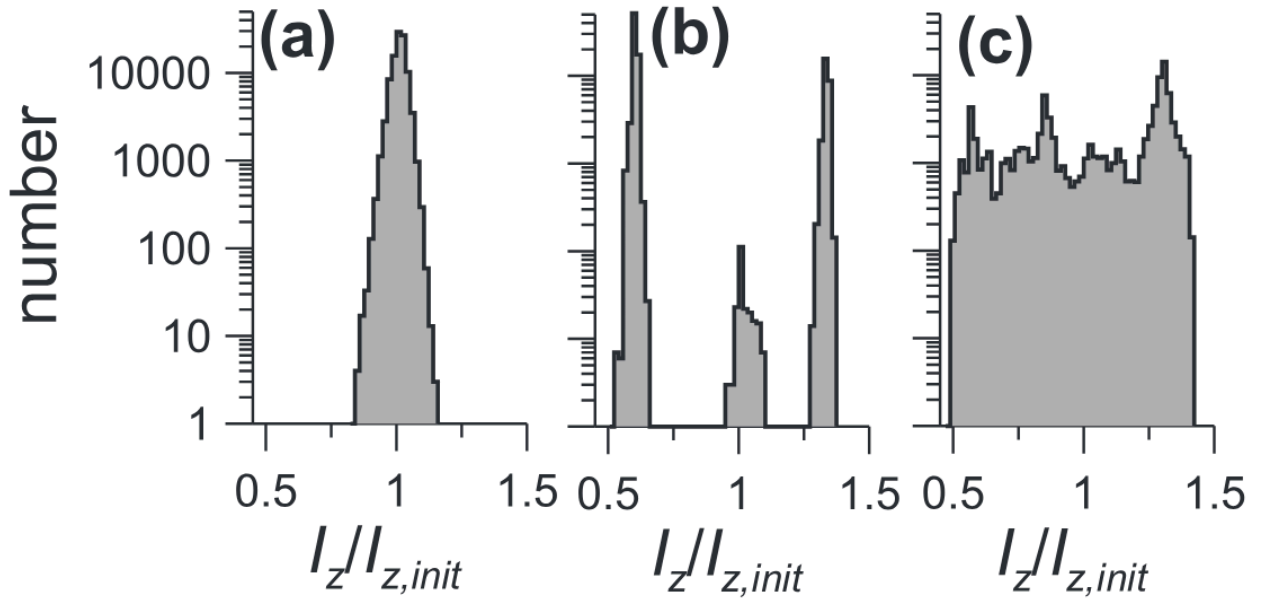


Figure 1.16: Distribution of I_z values for an ensemble of 10^5 trajectories after 10 separatrix crossings: (a) $s = 0$, $\varepsilon = 0$; (b) $s = 0.15$, $\varepsilon = 0$; (c) $s = 0.15$, $\varepsilon = 0.003$. All with $\kappa = 0.01$. From Artemyev et al. (2014).

1.4.2.7.4 Current sheet dynamics: particle reflection, transmission and resonance

These non-adiabatic effects also have several physically important consequences for current sheet dynamics. The guide field introduces an asymmetry in particle reflection and transmission at the current sheet boundaries. A. V. Artemyev et al. (2013) showed that for $B_y > 0$, particles approaching from the Southern Hemisphere ($z > 0$) are increasingly likely to transit through the sheet rather than be reflected, with transition becoming certain for $s > 0.35$ (i.e., $B_y > 0.35B_0\sqrt{L/\rho_0}$). Particles from the Northern Hemisphere ($z < 0$), by contrast, cross the sheet without any scattering for $s > (\pi^{-1} \ln 2)\kappa$, because the uncertainty curve shrinks and these particles never encounter the separatrix. This

directional asymmetry of current sheet interaction has implications for asymmetric auroral precipitation and for the self-consistent equilibrium of current sheets with finite guide fields.

The finite guide field also destroys the resonant condition under which two successive dynamical jumps can exactly compensate—a condition that, in the symmetric case, produces coherent beamlets of accelerated particles. For $s > (\pi^{-1} \ln 2)\kappa$, the resonance condition, $\sum \Delta I_z^{\text{dyn}} = 0$, cannot be simultaneously satisfied for a large particle population. Moreover, the dependence of the integral W on I_z steepens with increasing s , so that even if the resonance condition is satisfied at one value of I_z , particles with slightly different invariants are far from resonance. The coherent beamlet structures predicted for the symmetric system are thus disrupted.

1.4.2.8 Application to Force-Free Solar Wind Current Sheets: Superfast Scattering

The theoretical framework described above was applied to energetic ion scattering by solar wind discontinuities by Artemyev et al. (2020a). The key observation motivating that work is that the internal magnetic field structure of observed solar wind current sheets differs in an important way from the idealized models previously considered. In observed compressionless (force-free) discontinuities, the reversal of the maximum-variance component B_l is accompanied by a peak in the intermediate-variance component B_m , such that $|B| \approx \text{const}$ across the structure (as shown earlier in Figure 1.4 and confirmed statistically by Vasko et al. (2022)). This B_m peak was absent from earlier Hamiltonian models of ion–current sheet interaction, which assumed either $B_m = 0$ (pure field reversal) or $B_m = \text{const}$ (uniform guide field).

To account for this observed field configuration, Artemyev et al. (2020a) modeled the discontinuity magnetic field as $B_l \approx B_0(r_n/L)$, $B_n = \text{const}$, $B_m = \sqrt{B_0^2 - B_l^2} \approx B_0(1 - r_n^2/2L^2)$, which in the normalized Hamiltonian introduces a cubic term:

$$H = \frac{1}{2}p_z^2 + \frac{1}{2}\left(p_x - z + \frac{z^3}{6}\right)^2 + \frac{1}{2}\left(\kappa x - \frac{z^2}{2}\right)^2.$$

The $z^3/6$ term, which encodes the B_m peak, breaks the symmetry of the phase portrait in the (z, p_z) plane. This is the essential difference from the $p_x^2/2$ term (no B_m ; pure compressional discontinuity) or the $(p_x - z)^2/2$ term (constant B_m ; uniform guide field) used in previous studies. As demonstrated by the theory of geometrical chaotization (Artemyev et al., 2014), this asymmetry generates large geometrical jumps $\Delta I_z \sim 1$ at each separatrix crossing, producing very fast destruction of the adiabatic invariant.

This result has several important implications for energetic particle transport in the solar wind:

First, the scattering rate (measured in the slow time κt) is independent of $\kappa = (B_n/B_0)\sqrt{L/\rho}$. Since κ determines whether a discontinuity is classified as rotational (finite B_n) or tangential ($B_n \rightarrow 0$), this means that the distinction between RDs and nearly-TDs is irrelevant for the efficiency of ion scattering, provided the B_m peak is present. In a solar wind containing multiple discontinuities, the timescale between successive scattering events is determined by the occurrence rate of discontinuities rather than by κ , further reducing the importance of B_n .

Second, the condition for strong scattering is $L \sim \rho$, which can be rewritten in terms of particle energy as $h/T_i \sim \beta_i(L/d_p)^2$. For the most intense kinetic-scale discontinuities observed in the solar wind ($L/d_p \in [1, 10]$) and typical plasma conditions ($\beta_i \in [0.1, 10]$), this condition is satisfied for essentially the entire suprathermal ion population. The mechanism is therefore expected to operate broadly.

Third, test particle simulations confirmed that in the presence of the B_m peak, initially narrow distributions in both I_z and pitch angle broaden rapidly—within a few separatrix crossings—to fill a broad range. In contrast, when the B_m peak is absent ($B_m = 0$), the distributions remain narrowly peaked around their initial values, consistent with the much slower diffusive destruction of I_z in the symmetric system. The effect is robust for $B_m/B_0 > 0.75$, which encompasses the majority of observed force-free discontinuities.

The identification of this “superfast” scattering mechanism establishes that kinetic-scale current sheets in the solar wind are not merely passive structures but active agents of energetic particle scattering. This mechanism is expected to shape the observed low-

anisotropy ion distributions at 1 AU and to contribute significantly to cross-field transport of energetic particle populations. The quantitative characterization of this scattering—including the derivation of analytical pitch-angle diffusion coefficients informed by observed current sheet parameters—forms one of the central contributions of this thesis and is developed in the following chapters.

1.4.3 Summary and Open Questions

This chapter has established the theoretical and observational foundation for understanding energetic particle scattering by solar wind current sheets. We summarize the key points and identify the open questions that motivate the work presented in this thesis.

Solar wind turbulence is highly intermittent, with magnetic energy concentrating into current sheets whose thickness overlaps with the gyro-radii of suprathermal and energetic ions. When a particle’s gyroradius is comparable to the sheet thickness, guiding-center theory fails and the quasi-adiabatic invariant I_z governs the dynamics instead of the magnetic moment μ . This invariant is destroyed at separatrix crossings through two mechanisms: dynamical jumps, which drive slow diffusion on a timescale $\sim \kappa^{-3}$ (or $\sim \kappa^{-2}$ with a guide field), and geometrical jumps, which in asymmetric field configurations—including the force-free current sheets most commonly observed in the solar wind—produce order-unity changes in I_z within a single gyration. This *geometrical chaotization* constitutes a superfast scattering mechanism for energetic particles.

Observationally, current sheets modulate SEP intensities at both large and small scales. The heliospheric current sheet acts as a barrier to cross-hemisphere transport and drives systematic flux dropouts whose energy dependence is consistent with gyroradius-scale interactions. At kinetic scales, coherent magnetic structures are statistically correlated with sharp variations in energetic particle intensity. Together, these observations confirm that current sheets are not passive features of the background medium but active agents of particle scattering and transport.

Several important questions remain open and motivate the work in Chapter 4 and Chapter 5.

Pitch-angle diffusion coefficients from current sheet parameters. While the superfast scattering mechanism has been demonstrated theoretically and confirmed in test-particle simulations, a quantitative analytical expression for $D_{\mu\mu}$ as a function of particle energy and current sheet parameters has not yet been derived. Such an expression—informed by the observed statistical distributions of magnetic field configurations—is needed to incorporate current-sheet scattering into heliospheric transport models and constitutes a central goal of this thesis.

Perpendicular transport and cross-field diffusion. The role of current sheets in cross-field transport remains largely unexplored. Near current sheets, the magnetic field varies on scales comparable to or smaller than the gyroradius, enabling enhanced transfer of particles between field lines through a mechanism distinct from field-line random walk. The anti-correlation between large curvature and weak magnetic field strength (Kempski et al., 2023; Yang et al., 2019) further suggests that particles undergoing magnetic moment-violating interactions are simultaneously more likely to hop between field lines—a potentially important source of perpendicular transport that deserves systematic study in the solar wind context.

Chapter 2

Solar Wind Discontinuities in the Outer Heliosphere: Spatial Distribution Between 1 and 5 AU

Solar wind discontinuities (SWDs), commonly defined as localized and abrupt changes in the magnetic field (Colburn & Sonett, 1966), are mesoscale plasma structures with typical thicknesses on the order of ion kinetic scales and horizontal extensions that often exceed magnetohydrodynamic (MHD) scales. They are observed throughout the heliosphere, from the inner heliosphere (Liu et al., 2022a; Lotekar et al., 2022) to the heliosheath (Burlaga & Ness, 2011). Despite being discovered over half a century ago, their specific origins and the circumstances of their formation remain subjects of ongoing debate (Vasko et al., 2022; 2024, and references therein). Historically, SWDs were thought to originate inside 1 AU and to be passively convected outward by the solar wind (Borovsky, 2008; Söding et al., 2001; Tsurutani & Smith, 1979); however, waiting-time statistics consistent with MHD turbulence simulations suggest that a significant fraction arise spontaneously as boundaries between magnetic flux tubes, generated locally throughout the heliosphere (Greco et al., 2009). Both tangential and rotational discontinuity types are observed (Artemyev et al., 2019b; Neugebauer, 2006; Wang et al., 2024), which may originate differently and follow distinct evolutionary paths (Hudson, 1970). Investigating their properties across large heliocentric distances offers a direct test of these competing formation scenarios.

Investigation of the evolution of SWD properties with radial distance (or alternatively, investigation of properties of SWD generation at different radial distances) has mostly been limited to comparison of SWD statistics obtained from different missions during varying phases of solar activity (Mariani et al., 1973; Söding et al., 2001; Tsurutani & Smith, 1979). However, the data used in these studies were rarely compared with measurements at fixed radial distances, and the methods employed to identify discontinuities were not necessarily optimized for studying discontinuities with weak magnetic fields and long durations, such as those encountered at large radial distances. Furthermore, some measurements at different radial distances were significantly separated in time, with limited time ranges

covered (Söding et al., 2001). Consequently, there are still some ambiguities in interpreting the results of these studies. For example, it is unclear how much of the observed variation in SWD properties is caused by radial distance itself versus changing solar wind conditions. Characterizing the statistical properties of current sheets across heliocentric distance is also a prerequisite for the particle transport studies developed later in this thesis (Chapter 4 and Chapter 5), where the observed distributions of current sheet thickness, current density, and magnetic field configuration serve as input parameters for test-particle simulations.

This study presents a statistical analysis of discontinuities observed from Earth’s orbit (~ 1 AU) to Jupiter’s orbit (~ 5 AU). We utilize data collected by the Juno spacecraft (Bolton et al., 2017) during its cruise phases (2011-2016), with its orbits shown in Panel (a) of Figure 2.1. Our primary goal is to investigate the radial dependence of the SWD occurrence rate and properties to gain insights into their evolution and origin. Continuous measurements of SWDs at 1 AU from missions such as Wind (Acuña et al., 1995), ARTEMIS (Angelopoulos, 2011), and STEREO (Kaiser et al., 2008) have been utilized to distinguish temporal effects from spatial variations by examining the characteristics of discontinuities at two radial distances (1 AU and at Juno location) simultaneously. This distinction is crucial because temporal variations could easily be misinterpreted as spatial variations (Tsurutani & Smith, 1979). Due to the potential misidentification of the SWD normal direction with single spacecraft (Hausman et al., 2004; Liu et al., 2023; Wang et al., 2024), we do not differentiate between shocks and different types of discontinuities, whether they are tangential, rotational, or either (Neugebauer et al., 1984).

The chapter is structured as follows. First, we outline the missions, instruments, and data utilized in this study (Section 2.1.1). Next, we briefly describe the method used to identify discontinuities and the model employed to estimate the plasma state at the Juno location, necessitated by the absence of plasma data during its cruise phase (Section 2.1.2). In Section 2.2, we present the results concerning the spatial variation of discontinuities, focusing on their occurrence rate and characteristics, such as their spatial scales and current density. Finally in Section 2.3, we discuss the implications of our findings in the context of the origin and evolution of these discontinuities in the solar wind.

2.1 Dataset, Models, and Methods

Figure 2.1 provides an overview of Juno’s cruise phase (2011-2016) and the corresponding solar wind conditions. The solar wind plasma state, as evidenced by the sunspot number (shown in Panel (c)), plays a crucial role in understanding the dynamics of discontinuities. Early in the Juno mission (Bolton et al., 2017), the sunspot numbers reached a peak, indicating a period of increased solar activity. By 2016, however, they had declined significantly. This variation underscores the need to account for temporal, solar-cycle-related variability when calibrating and interpreting discontinuity properties.

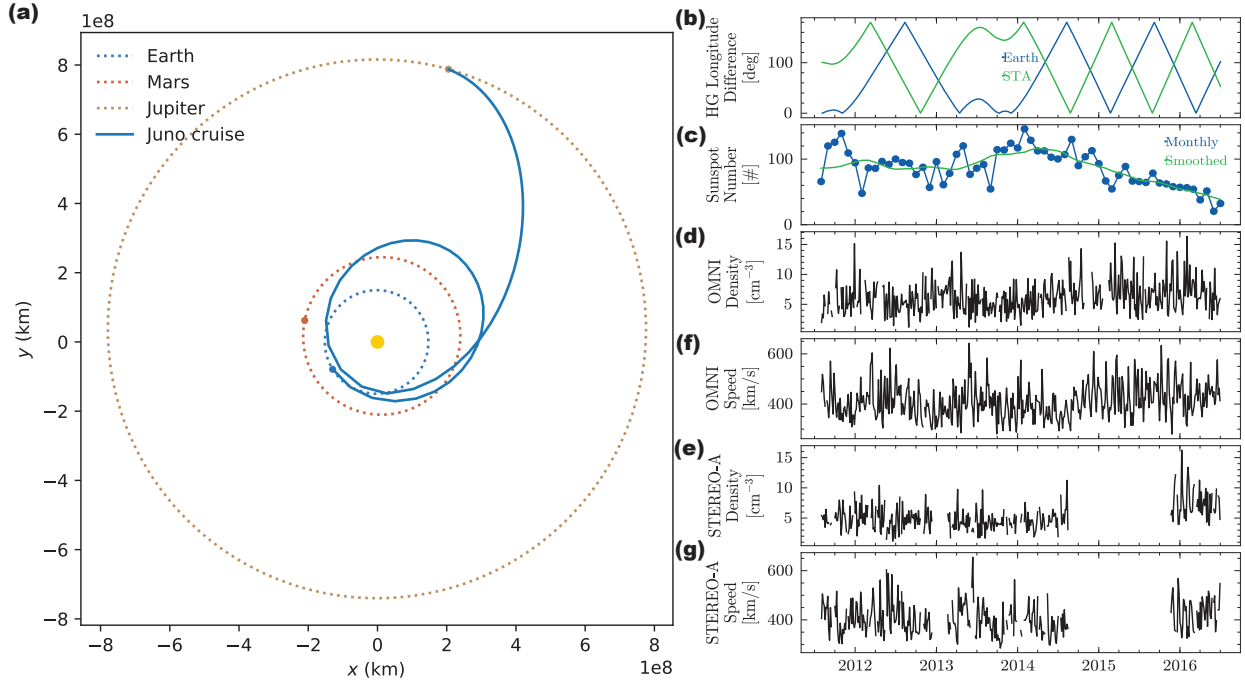


Figure 2.1: Overview. **(a)** Juno’s orbit during its cruise phase (2011-2016). **(b)** Absolute difference in heliographic longitude between Juno and Earth (blue) and between Juno and Stereo-A (STA, green). **(c)** Monthly and smoothed sunspot numbers. **(d-g)** Solar wind plasma density and speed from Near-Earth (OMNI) and STEREO-A missions.

Figure 2.1 (b) shows the heliographic longitudinal difference between Juno and Earth, and between Juno and STEREO-A. Notably, when there is a substantial longitudinal difference between Juno and Earth, the difference between Juno and STEREO-A tends to be minimal, and vice versa. This complementarity allows us to compare SWD behavior at 1 AU and further outward at Juno with minimal absolute longitudinal separations $<$

120°, alternating between Earth and STEREO-A as the SWD observational platform at 1 AU.

2.1.1 Dataset

We analyze Juno’s observations during its cruise phase from August 25, 2011, to July 30, 2016, spanning approximately 1,800 days. Data from missions such as STEREO, ARTEMIS (THEMIS-B/C), and Wind complement Juno’s observations, providing a broader perspective on heliospheric conditions and enabling multi-point analysis of discontinuity properties (Velli et al., 2020). Specifically, we utilize magnetic field measurements from Juno’s Fluxgate Magnetometer instrument (Bolton et al., 2017; Connerney et al., 2017) and solar wind parameters from the ion sensor of the Jovian Auroral Distributions Experiment (JADE) (McComas et al., 2017). For ARTEMIS (Angelopoulos, 2011), we use magnetic field data from its Fluxgate Magnetometer instrument (Auster et al., 2008) and ion bulk velocity and plasma density from the Electrostatic Analyzer instrument (McFadden et al., 2009). For STEREO (Kaiser et al., 2008), we incorporate magnetic fields from the magnetic field experiment on IMPACT (Acuña et al., 2008; Luhmann et al., 2008) and ion bulk velocity and plasma density from PLASTIC (Galvin et al., 2008). For Wind (Acuña et al., 1995), we include magnetic fields from the Magnetic Field Investigation instrument (Lepping et al., 1995), ion bulk velocity, and plasma density from the Solar Wind Experiment instrument (Ogilvie et al., 1995). The time resolution of magnetic field and plasma data varies across the missions analyzed in this study. We use magnetic field data from Juno at 1 Sample/S (S/s), ARTEMIS at 5 S/s, Wind at 11 S/s, and STEREO at 8 S/s. We use plasma data from ARTEMIS at 0.25 S/s, Wind at 0.33 S/s, and STEREO at 1-minute intervals. To ensure the robustness of our results, we employ methods (to be introduced in the next section) that are specifically designed to minimize the influence of time resolution on the identification of current sheets and the calculation of their properties. These synergistic multi-satellite observations provide a comprehensive perspective on solar wind discontinuities, enabling the analysis of their radial distribution and temporal evolution. The data access, processing, and analysis infrastructure supporting this multi-mission survey is described in Appendix B.

Since in-situ measurements from JADE are only available for the final 40 days of its cruise phase prior to Jupiter arrival (Wilson et al., 2018), we rely on solar wind propagation models to estimate the thickness and current density of discontinuities for the remainder of the cruise. A direct comparison between the modeled solar wind properties and JADE observations during the overlapping interval is presented in Panels (a-d) of Figure 2.9 in the Appendix. Specifically, we employ the Two-Dimensional Outer Heliosphere Solar Wind Modeling (MSWIM2D) (Keebler et al., 2022) to determine the ion bulk velocity (v) and plasma density (n) at Juno’s location. This model, which utilizes the BATSRUS MHD solver (Tóth et al., 2012), simulates the propagation of the solar wind from 1 to 75 astronomical units (AU) in the ecliptic plane, effectively covering the region pertinent to our study. The MSWIM2D model provides output data with an hourly time resolution, as shown in Figure 2.2. After averaging Juno data to the same time resolution, comparing magnetic field magnitudes from MSWIM2D with those of Juno reveals a strong correlation, confirming the model’s applicability to our study.

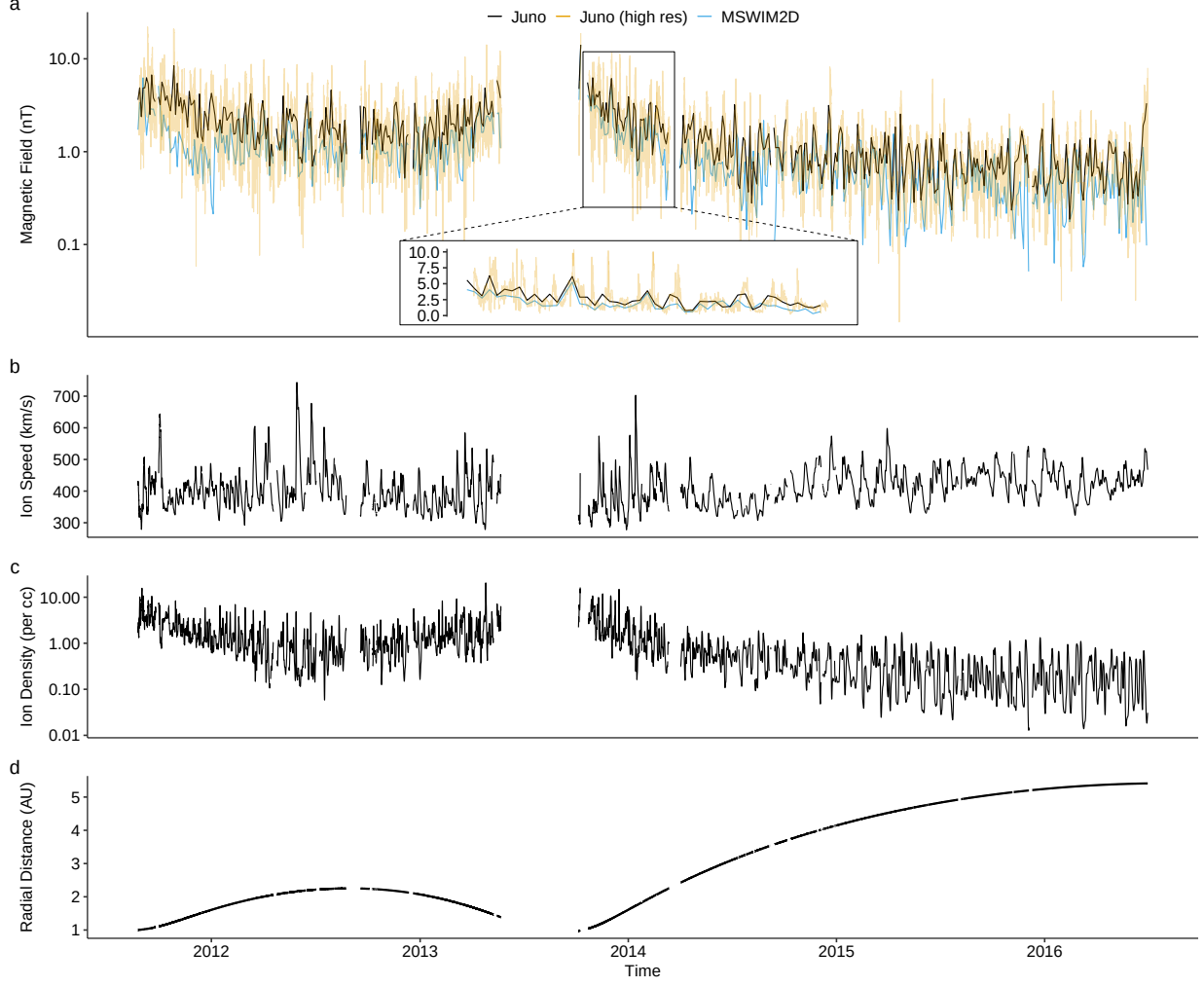


Figure 2.2: **(a)** Magnetic field magnitude from MSWIM2D and Juno. **(b-c)** Plasma speed and density from MSWIM2D model. **(d)** Juno radial distance from the Sun.

2.1.2 Methods

We employ the method of Liu et al. (2022b) to identify discontinuities in the solar wind. This method is better suited for discontinuities with small magnetic field changes and is more robust for conditions in the outer heliosphere compared to traditional methods, namely the B -criterion (Burlaga, 1969) and the TS -criterion (Tsurutani & Smith, 1979). For each sampling time t , we define three intervals: the pre-interval $[-1, -1/2] \cdot T + t$, the middle interval $[-1/2, 1/2] \cdot T + t$, and the post-interval $[1/2, 1] \cdot T + t$, where T represents time lags. The magnetic field time series in these three intervals are labeled as $\mathbf{B}_-$, $\mathbf{B}_0$,

and $\mathbf{B}_+$, respectively. We first apply the following three detection criteria to establish the time interval that encompasses each discontinuity candidate:

$$\begin{aligned}\sigma(\mathbf{B}_0) &> 2 \max(\sigma(\mathbf{B}_-), \sigma(\mathbf{B}_+)) \\ \sigma(\mathbf{B}_- + \mathbf{B}_+) &> \sigma(\mathbf{B}_-) + \sigma(\mathbf{B}_+) \\ |\Delta \mathbf{B}| &> |\mathbf{B}_{bg}| / 10\end{aligned}$$

Here, σ denotes the standard deviation, $\mathbf{B}_{bg}$ represents the background magnetic field magnitude, and $\Delta \mathbf{B} = \mathbf{B}(t + T/2) - \mathbf{B}(t - T/2)$. The first two conditions ensure that the field changes are distinguishable from stochastic fluctuations, while the third condition serves as a supplementary measure to reduce recognition uncertainty (Liu et al., 2022b).

Notably, this method shares certain similarities with the Partial Variance of Increments (PVI) approach (Greco et al., 2017) for identifying coherent structures, since both calculate indices based on standard deviations (with this method focusing on the standard deviation of the magnetic field while PVI focuses on magnetic field increments). However, the method of Liu et al. (2022b) is better suited for discontinuity identification by comparing data within neighboring time windows rather than across a correlation scale (a quantity used in the PVI method that may vary with radial distance and solar wind conditions). As a result, this approach effectively excludes wave-like coherent structures, eliminating the need for manual inspection. Additionally, PVI generates discrete data points at each time step, which subsequently require an additional processing step\{ \} grouping consecutive points exceeding a threshold into continuous event clusters, thereby converting individual timestamps into contiguous time ranges. In contrast, our method inherently outputs the time ranges of interest without this additional step.

Because discontinuities may exhibit different spatial scales at varying radial distances from the Sun, we conducted the identification procedure using multiple time lags ($T = 20, 30, 40, 50, 60$ s). The resulting events from each search were then combined into a comprehensive final list, removing any duplicates. The choice of a 20-second lower limit was driven by the typical sampling rate (~ 1 sample/s) of the Juno spacecraft. However, it should be noted that shorter-duration discontinuities may be underrepresented, particularly near 1 AU. This limitation becomes less significant as Juno travels to greater radial

distances, where discontinuities generally exhibit longer durations. Discontinuities with spatial scales exceeding 60 seconds were not considered in this analysis. Nonetheless, such large-scale discontinuities are expected to be relatively rare in the outer heliosphere, as previous studies indicate a decreasing frequency of SWDs with increasing spatial scale (Vasko et al., 2022; 2024).

More than 130,000 SWD intervals have been identified in the solar wind data from Juno, with approximately 17,000 intervals detected within [4, 5] AU. After identifying each discontinuity candidate, we construct a distance matrix using the magnetic field sequence (Dokmanic et al., 2015) to determine the leading edge and trailing edge of the discontinuity within this preliminary interval. Specifically, we define the distance between two magnetic field vectors $\mathbf{B}(t_a)$ and $\mathbf{B}(t_b)$ as the Euclidean norm of their difference: $d(a, b) = \|\mathbf{B}(t_a) - \mathbf{B}(t_b)\|$. We locate the leading edge at t_a and the trailing edge at t_b such that $t_a < t_b$ and $d(a, b)$ attains its maximum value within the time interval under consideration. After that, we use the minimum variance analysis (MVA) (Sonnerup & Cahill Jr., 1967; Sonnerup & Scheible, 1998) to transform the magnetic field into the boundary normal (LMN) coordinate system. Then, the maximum variance (main) component, B_l , is fitted with a hyperbolic tangent to extract parameters characterizing the discontinuity, inspired by the standard Harris current sheet model (Harris, 1962):

$$B_l(t) = B_{l,i} \tanh\left(\frac{t - t_i}{\Delta t_i}\right) + c_i \quad (4)$$

where $B_{l,i}$ is the amplitude of the magnetic field change in the maximum variance direction, t_i is the detection time, Δt_i is the transit time, and c_i is the offset of the magnetic field change for the i -th discontinuity event. While c_i should theoretically be zero for an ideal rotational discontinuity, it may not necessarily be zero for tangential discontinuities or shocks. Nonetheless, including c_i in data processing enhances the fitting accuracy. Finally, we combine the magnetic field data and plasma data (from the model) to obtain the thickness and current density of the discontinuity.

Assuming that the SWD structures are planar, the normal direction can be obtained by minimizing the variance of the magnetic field's normal component in MVA. However, previous studies have indicated that the normal direction obtained through MVA is frequently

unreliable (Knetter et al., 2004; Wang et al., 2024). Improved accuracy can be achieved by either using the cross product of the magnetic field measured at the boundaries as the normal direction (Knetter et al., 2004) or by enforcing conditions such as $\Delta |\mathbf{B}| / |\mathbf{B}| > 0.05$ or $\omega > 60^\circ$ (Liu et al., 2023), where $\Delta |\mathbf{B}|$ is the change in the magnitude of the magnetic field and ω is the field rotation angle across the discontinuity. The former approach requires a small magnetic field component (B_n) along the discontinuity normal, while the latter approach limits the dataset to a subset that satisfies these conditions. These two methods yield closely aligned normal directions when B_n is small and either $\Delta |\mathbf{B}| / |\mathbf{B}| > 0.05$ or $\omega > 60^\circ$ is satisfied. In our analysis, we applied both techniques and found that they yielded statistically consistent results. A direct comparison of the discontinuity properties obtained from these two methods is presented in panels (e-j) of Figure 2.9 in the Appendix, using intervals from Juno’s approach to Jupiter when solar wind parameters were available.

Figure 2.3 shows several examples of solar wind discontinuities detected by different spacecraft. Panels (a-c) show three examples of SWDs observed by Juno at 1, 3, and 5 AU distances, whereas Panels (d-f) show three examples of SWDs observed by Wind, ARTEMIS, and STEREO-A (for these three, we also show solar wind flow speed). All discontinuities share the same magnetic field configuration (in local LMN coordinates): the main magnetic field component, B_l , reverses sign across the discontinuity, whereas the decrease of the magnetic pressure, $\sim B_l^2/2\mu_0$, is compensated by local enhancement of B_m component. Such magnetic field rotation across the discontinuity keeps $|\mathbf{B}|$ almost constant (Artemyev et al., 2019a; Lotekar et al., 2022; Vasko et al., 2022; 2024). The solar wind flow speed (three panels for Wind, THEMIS-B, and STEREO-A) shows a typical jump across the discontinuities (Artemyev et al., 2020b).

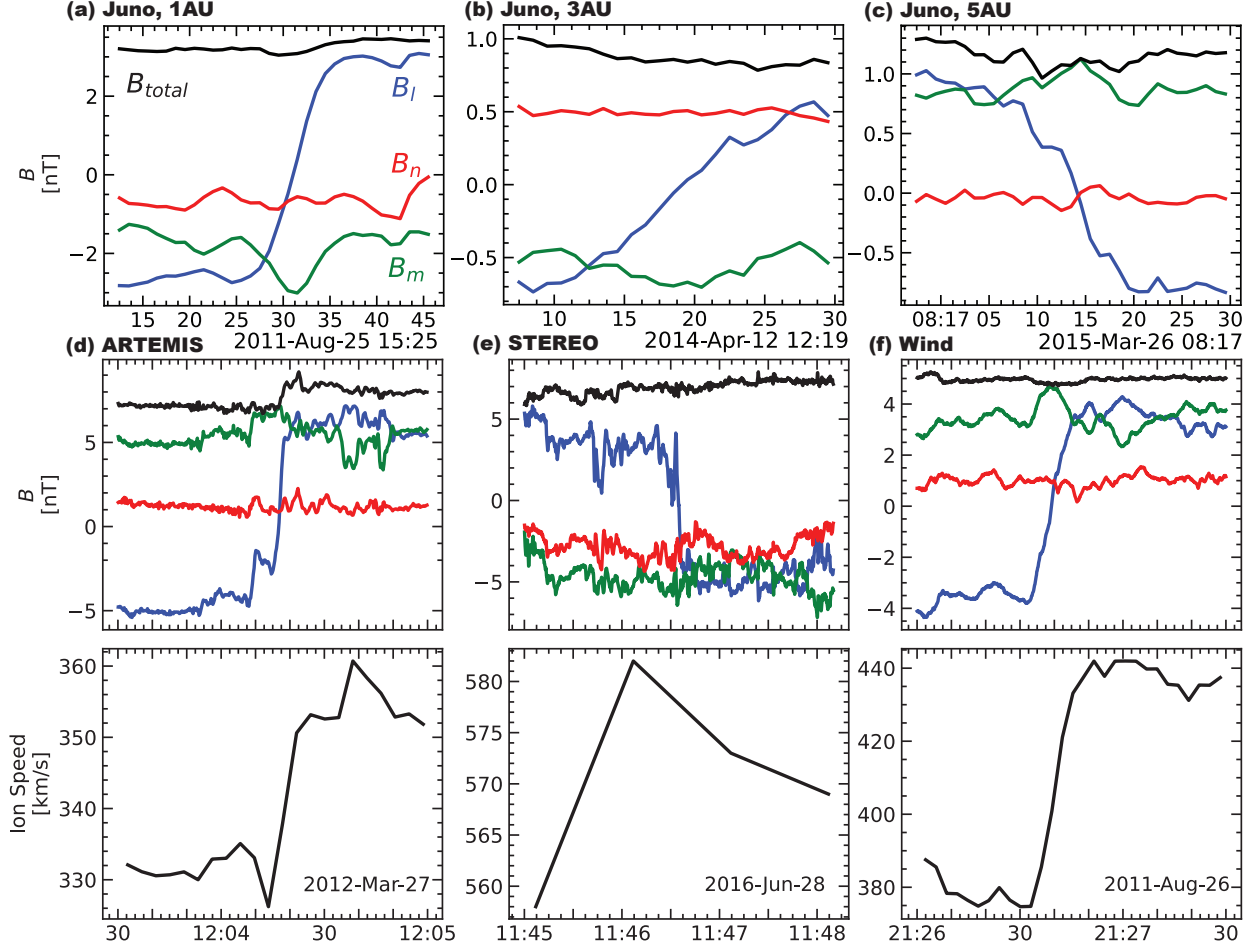


Figure 2.3: Examples of solar wind discontinuities observed by various spacecraft at different heliocentric distances and times. Panels (a)–(c) display data from Juno at 1 AU (a), 3 AU (b), and 5 AU (c), showing magnetic field components B_l (blue), B_n (red), B_m (green), and the magnetic field magnitude B_{total} (black). Panels (d)–(f) show magnetic field and ion speed observations at 1 AU from other spacecraft: THEMIS-B (ARTEMIS) on March 27, 2012 (d), STEREO-A on June 28, 2016 (e), and Wind on August 26, 2011 (f).

2.2 Results

2.2.1 Waiting Time

To fully understand the radial evolution of the SWD occurrence rate, particularly the average occurrence rate, it is essential to examine the statistical distributions underlying the observed SWD samples. In this regard, we derive the probability distribution of

the waiting time $\tau = t_i - t_{i-1}$, where t_i is the detection time for the i -th event from Equation 4, sorted in ascending order (τ is also referred to as the interarrival interval, e.g., by Tsurutani & Smith (1979)). We employ the Weibull distribution (Weibull, 1951) for its flexibility in capturing varying occurrence rates. This choice allows for a more accurate representation and improved fit compared to the exponential distribution previously used by Tsurutani & Smith (1979). The probability density function of the Weibull distribution is given as follows:

$$f(\tau; \alpha, \theta) = \frac{\alpha}{\theta} \left(\frac{\tau}{\theta} \right)^{\alpha-1} e^{-(\tau/\theta)^\alpha}, \quad \tau \geq 0$$

where α and θ represent the shape and scale parameters, respectively. The complementary cumulative distribution function of the Weibull distribution $F(\tau; \alpha, \theta) = 1 - e^{-(\tau/\theta)^\alpha}$ is a stretched exponential function (the Weibull distribution reduces to the exponential distribution when $\alpha = 1$).

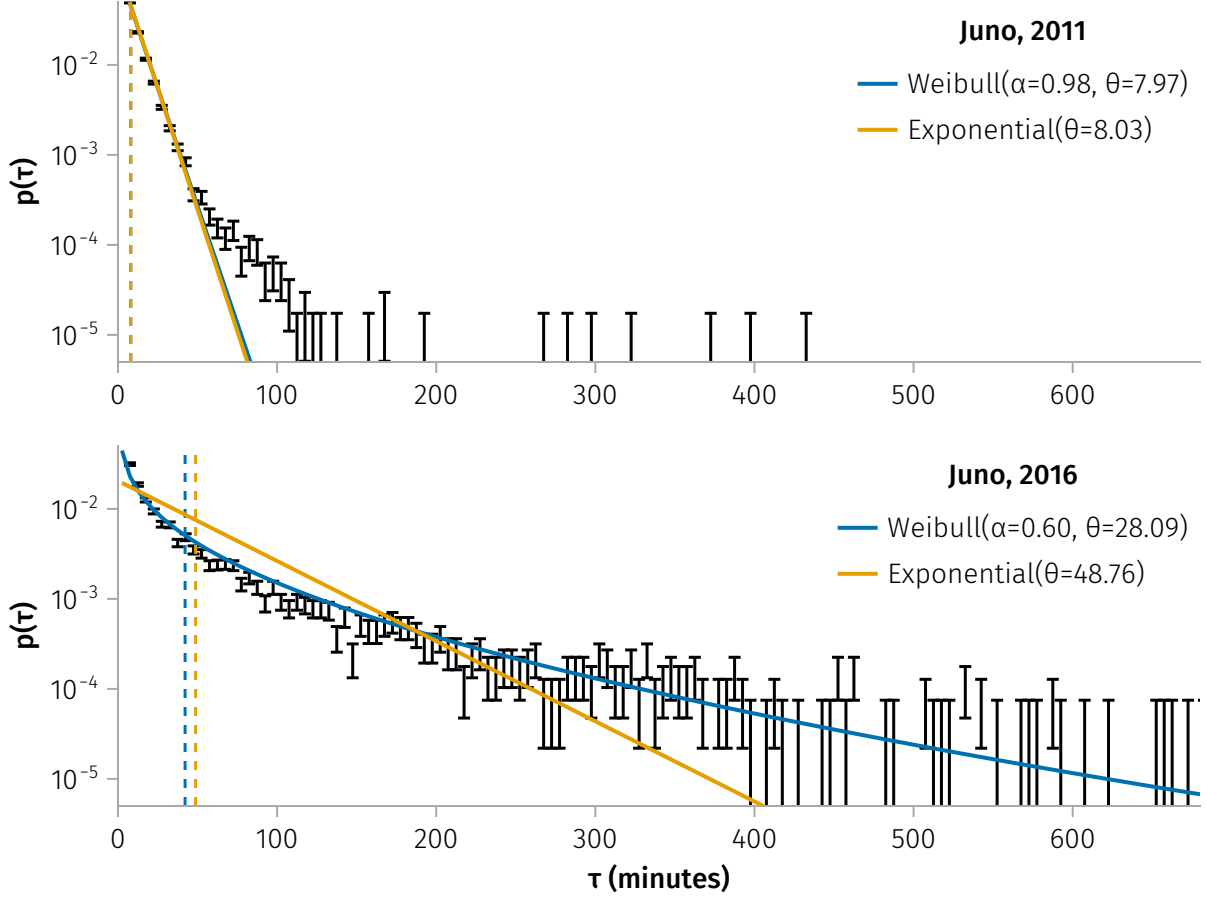


Figure 2.4: Waiting time probability density functions $p(\tau)$ for Juno at 1 AU in 2011 (top) and 5 AU in 2016 (bottom). Observed data (black) are fitted with Weibull (blue) and exponential (orange) distributions. Vertical dashed lines denote the mean waiting times for each fitted distribution.

The observed waiting time distribution, along with the fitted distribution, is shown in Figure 2.4. For $\alpha < 1$, the probability of observing longer waiting times is higher than would be expected from a purely exponential distribution. This indicates that the occurrence rate of discontinuities is not constant, but rather varies with time - likely reflecting the evolving state of the solar wind (see the discussion in Tsurutani & Smith (1979)). Across the largest range of waiting times, the observed probabilities exceed those modeled by the fitted distribution. This may be due to data gaps that artificially extend the observed waiting times between discontinuities.

The mean waiting time, $\bar{\tau}$, can be determined by integrating the probability density function $\bar{\tau} = \int_0^\infty \tau f(\tau) d\tau$. The mean occurrence rate, in turn, is simply the reciprocal of the mean waiting time. At 1 AU, the occurrence rate is approximately 150 events per day,

while at 5 AU, Juno observes around 30 events per day. These are consistent with previous results reported by Vasko et al. (2021); Vasko et al. (2024). Importantly, the mean value derived from the fitted Weibull distribution is more reliable, as it reduces the impact of unusually long waiting times often caused by data gaps.

2.2.2 Occurrence Rate

The occurrence rate of SWDs (number of events per effective observation time) is investigated for Juno, ARTEMIS, STEREO, and Wind. Figure 2.5 shows the number of discontinuities detected per effective day for each mission, using the same identification criteria ($T = 60s$). Because data are not continuously available on all satellites, the occurrence rate is corrected to account for data gaps. For ARTEMIS, an additional correction is needed because it only observes the pristine solar wind when the Moon is outside Earth’s magnetosphere - roughly 30% of its orbit is spent within the magnetosphere, and additional time can be spent in the lunar wake if apoapsis aligns with that region. After these corrections, ARTEMIS shows an occurrence rate comparable to Wind and STEREO for similar solar wind conditions.

The SWD occurrence rate observed by Juno is consistent with the occurrence rate observed by 1-AU missions when Juno is around 1 AU. This number decreases with distance as Juno moves from 1 AU to 5 AU (corresponding to time after ~ 2014 ; the radial distance of Juno for 2011-2016 is shown in Figure 2.2).

The occurrence rate depends linearly on the solar wind velocity (Söding et al., 2001); however, plasma velocity data from Juno are not available during its cruise phase. Therefore, we do not normalize the occurrence rate with respect to the solar wind speed. This influence of the solar wind speed on the occurrence rate might be mitigated by the fact that all spacecraft are in the ecliptic plane, and the solar wind speed is not expected to change significantly with radial distance from the Sun beyond 1 AU. We normalize the occurrence rate from Juno to the occurrence rate from 1-AU missions to account for the effect of solar wind structures on the occurrence rate.

The normalized occurrence rate is shown in Panel (b) of Figure 2.5. The occurrence rate of SWDs drops with the radial distance from the Sun, following a $1/r$ law. Spacecraft at ~ 1 AU record a steady rate over the same interval, indicating that solar-wind temporal variability cannot explain this trend. Instead, the observed decrease in the occurrence rate is a result of the increasing radial distance from the Sun (likely due to the geometric spreading of discontinuities across expanding spherical shells, see discussion below) and confirms previous results (Söding et al., 2001).

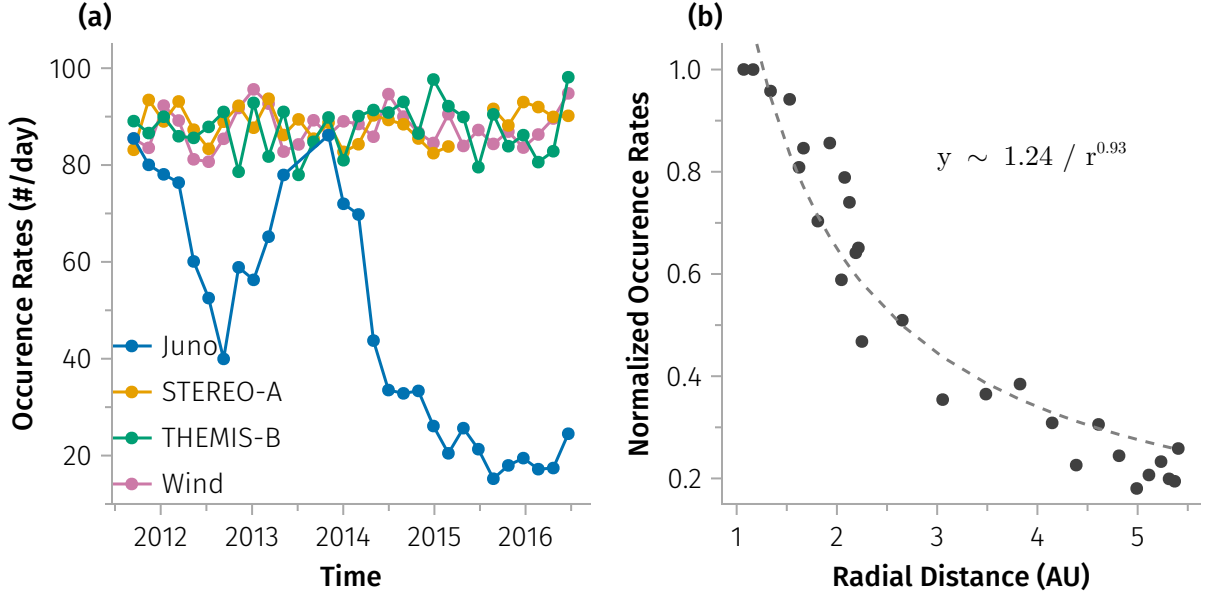


Figure 2.5: Left: the occurrence rate of discontinuities measured by Juno, STEREO-A, THEMIS-B, and Wind. Right: the normalized occurrence rate as a function of radial distance, where the radial distance of Juno for 2011-2016 is shown in Figure 2.2(d).

2.2.3 Current Density and Thickness

The current density J_m associated with the main magnetic field reversal across a discontinuity is determined by

$$J_m = -\frac{1}{\mu_0 V_n} \frac{dB_l}{dt}, \quad (5)$$

where μ_0 is the vacuum permeability and V_n is the normal component of the proton flow velocity. In the context of our fitting method, the derivative of the magnetic field

can be estimated as $\max(dB_l/dt) = B_{l,i}/\Delta t$. This estimate is more robust than directly differentiating the magnetic field, because the fitting method is less sensitive to the noise in the data and the time resolution of the data. Since the normal direction from the MVA method can be unreliable, we also compute an alternative velocity, $V_{nm} = \sqrt{V^2 - V_l^2}$, as an upper limit for V_n . We check that using either the MVA-derived V_n or this upper bound V_{nm} to estimate J_m and subsequent d leads to very similar results.

The thickness d of a discontinuity is determined by $d = V_n \Delta t$, where Δt is the transit time derived from the fitting method.

To understand the relationship between the discontinuity and the local plasma, we normalize the discontinuity thickness by the ion (proton) inertial length, $d_i = c/\omega_{pi}$, and the current density by the Alfvén current density, $J_A = eNV_A = B/\mu_0 d_i$, both of which represent natural plasma scales. The ion inertial length characterizes the scale at which ions decouple from the magnetic field, while the Alfvén current density corresponds to the characteristic current generated by the relative drift between electrons and ions moving at the local Alfvén speed V_A , particularly relevant in the context of MHD turbulence and reconnection studies (Franci et al., 2017; Zhdankin et al., 2013). Figure 2.6 presents these quantities for the SWDs measured by Juno and grouped by their radial distance from the Sun. Panels (a,c) show that the thickness increases with radial distance. However, after normalization, the thickness slightly decreases, with the most probable value around 2-4 d_i . With increasing radial distance, a larger fraction of SWDs exhibit thicknesses less than 1 d_i , transitioning into sub-proton scale structures. Panels (b,d) show that the current density decreases with increasing radial distance. However, after normalization, it slightly increases with radial distance, with the most probable value around 0.05-0.15 J_A . It should be noted that the variation of normalized thickness and current density with radial distance is not significant compared to the overall spread of their distributions (Vasko et al., 2024).

Figure 2.7 presents the thickness and current density distributions of the SWDs observed by 1-AU satellites (Wind, ARTEMIS, and STEREO-A) during the five-year Juno cruise phase. They are grouped by year of observation. Panels (a,c) show that the distributions of the thickness and normalized thickness of SWDs remain almost constant with the year of observation. Most discontinuities have thicknesses around 350-3500 km at 1 AU, with the

most probable value around 1000 km. Panel (b) shows that the current density increases slightly with the year of observation, with the most probable value remaining around 5 nA/m^2 , consistent with previous studies (Vasko et al., 2022). However, the year-to-year variation is weak and lies well within the overall variance of the distribution. This modest trend may be associated with gradual changes in solar wind conditions over the solar cycle, as illustrated in Figure 2.8. Toward solar minimum, the average magnetic field strength and the fitted magnetic field associated with discontinuities tend to increase slightly, but these changes are not statistically significant. Consequently, a weak upward trend in current density is observed. This pattern suggests that the apparent increase in current density and Alfvénic current density may reflect broader solar cycle variations while the normalized current density remains statistically stable, as shown in Figure 2.7(d).

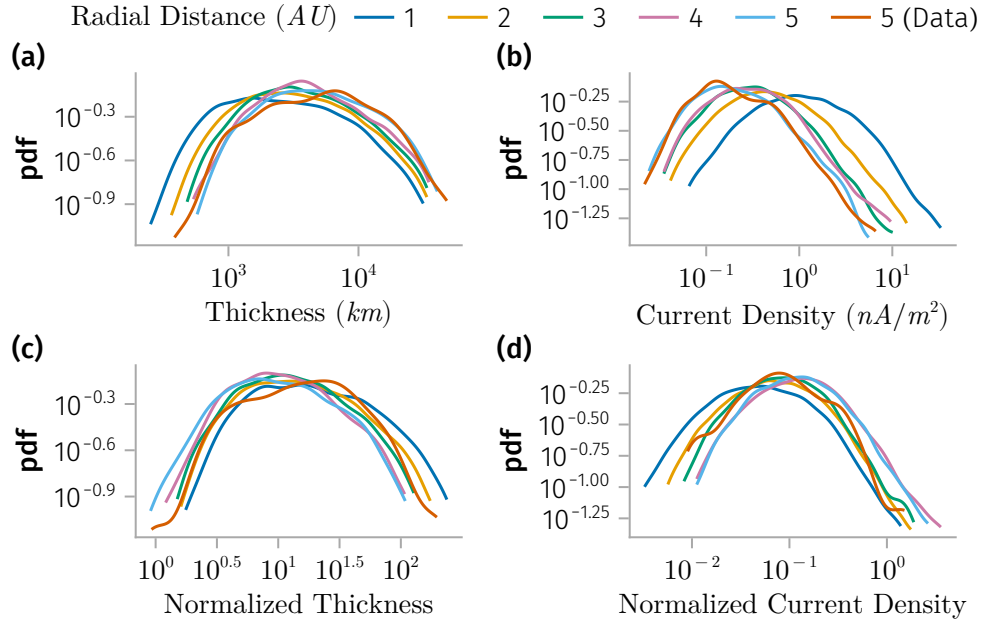


Figure 2.6: Distribution of various properties of SWDs observed by Juno, grouped by radial distance from the Sun (with color coding shown at the top). The label data indicates distributions calculated using solar wind properties from JADE observations rather than model predictions. Panels show: (a) discontinuity thickness, (b) current density, (c) normalized thickness, and (d) normalized current density.

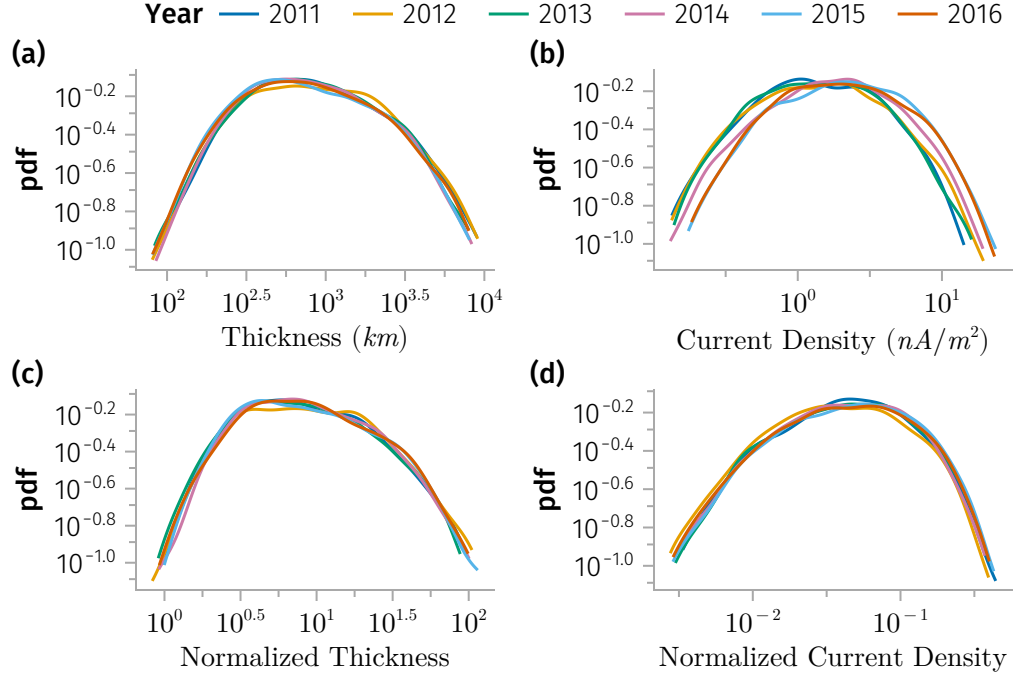


Figure 2.7: Distribution of various properties of SWDs observed by 1-AU satellites (Wind, ARTEMIS and STEREO-A), grouped by the year of observation (with colors shown at the top). Panel (a) thickness, (b) current density, (c) normalized thickness, (d) normalized current density.

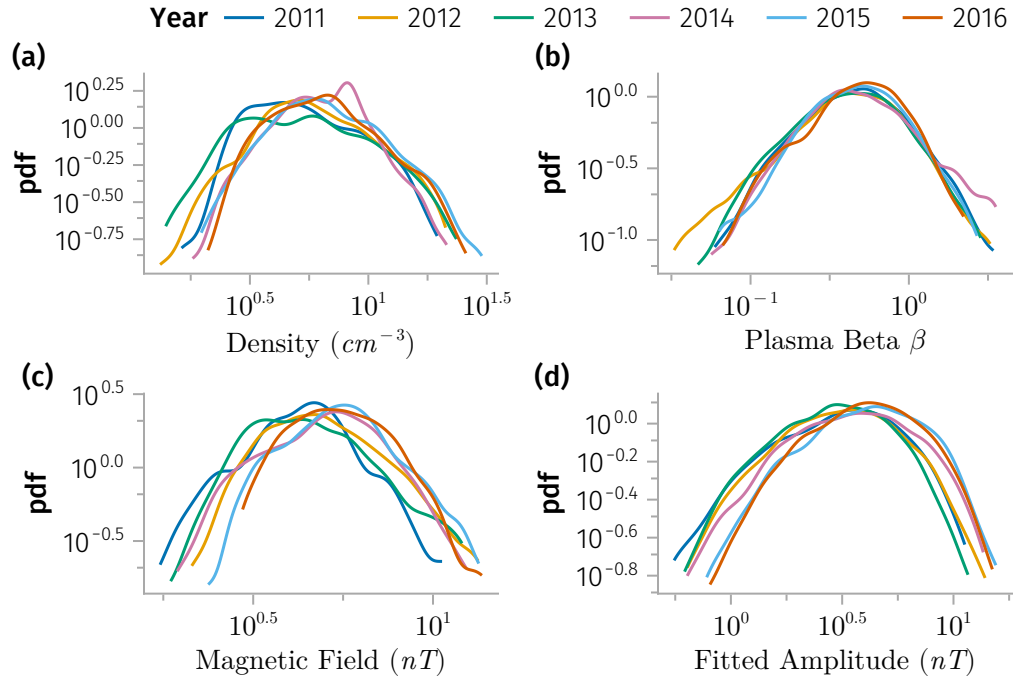


Figure 2.8: Solar wind parameters associated with the SWDs observed by 1-AU satellites (Wind, ARTEMIS and STEREO-A) grouped by the year of observation. Panel (a) solar wind density, (b), plasma beta, (c) magnetic field, (d) fitted magnetic field $B_{t,i}$ in Equation Equation 4.

2.3 Discussion

2.3.1 Spatial Variations of Discontinuity Properties

Continuous Juno observations of SWDs between 1 and 5 AU demonstrate a clear variation of their properties (thickness and current density magnitude) with radial distance. These results agree with and extend the previous statistics collected by different missions at different radial distances (Liu et al., 2021; Lotekar et al., 2022; Söding et al., 2001; Vasko et al., 2022; 2024). The current sheet spatial scale (thickness) increases with radial distance $d \propto r$, and scales with the local ion inertial length $d_i \propto 1/\sqrt{N_p} \propto r$. Meanwhile, the current density decreases with radial distance, scaling with the local Alfvén current density $J_A = eN_p V_A \propto B\sqrt{N_p} \propto B/r$. Here, the magnitude of the local magnetic field B evolves with radial distance in a manner similar to that of the interplanetary magnetic field, which generally follows $B \propto 1/r$. Consequently, the current density decays as $J \propto 1/r^2$, and this rate is consistent with the proportionality $J \propto B/d \propto 1/r^2$. The observed scaling relationship, $d \propto d_i$, can be interpreted as evidence supporting the local generation of SWDs. However, the same scaling is also expected for solutions of the kinetic nonlinear Schrödinger equation describing SWD formation as a result of nonlinear dynamics of Alfvén waves (Medvedev et al., 1997; Medvedev & Diamond, 1996). Thus, if the adiabatic evolution of SWDs follows this equation, it is expected that the scaling $d \propto d_i$ would be observed for SWDs propagating with the solar wind.

2.3.2 Radial Dependence of Occurrence Rate

The observed increase in the average waiting time (time between two discontinuities) with radial distance prompts us to explore different hypotheses to explain this phenomenon. At any given radial distance, discontinuities may originate from two primary sources: those generated near the Sun and convected outward by the solar wind and those formed locally.

First, we consider the limitations of our method for SWD detection. An increase in the duration (thickness) of discontinuities may render some unidentifiable if their duration becomes comparable to the time interval used in our analysis, T . Although we observe

a slight increase in the average duration of discontinuities with radial distance, this increase is relatively small. The overall population of discontinuities is still predominantly characterized by those with short durations, typically less than 20 seconds - which are effectively captured with $T = 20$ seconds (see Figure 2.10 in the Appendix). Although increasing T beyond 60 seconds may capture a few additional events, their number remains small. Importantly, our conclusions are not sensitive to a single T value; instead, the critical factor is the broad coverage provided by the range of T . In addition, since our method normalizes the change in the magnetic field relative to the surrounding field, any overall drop in the magnetic field magnitude with radial distance does not itself remove potential discontinuities from detection. Thus, it is unlikely that our methodology causes the observed decrease in occurrence rate at larger radial distances.

If most discontinuities are generated locally, their generation mechanism should depend on plasma parameters, mainly plasma β (Chen et al., 2014; Franci et al., 2016). This dependence might potentially explain the variation of the discontinuity occurrence rate with radial distance. To test this hypothesis, we examine the relationship between waiting time τ and β . We use the Wind spacecraft at 1 AU and calculate the average plasma beta $\bar{\beta} = (\beta_i + \beta_{i-1})/2$, where β_i is the plasma beta of the i -th discontinuity event. However, even at a 99% statistical significance level, the results of our analysis do not provide sufficient evidence to reject the null hypothesis that these two variables $\tau, \bar{\beta}$ are independent. Therefore, if discontinuities are generated primarily locally, factors other than plasma beta must influence their generation rates.

Alternatively, we consider the hypothesis that the majority of discontinuities are generated close to the Sun and then transported outward by the solar wind (since the solar wind speed is significantly higher than the Alfvén speed—which characterizes the propagation speed of rotational discontinuities—the fraction of inward-propagating to outward-propagating discontinuities is expected to be negligible). To estimate the total number of discontinuities in a spherical shell around the Sun at radius r , we account for the fact that a spacecraft observes only a subset of all existing structures - specifically, those whose projected surface area intersects its trajectory. Assuming that discontinuities are planar structures oriented at an angle $\theta_{n,v}$ with respect to the solar wind flow (an orientation shaped by the Archimedean Parker spiral), the effective surface area they present to the spacecraft is

given by $A_{eff} \sim wl \sin \theta_{n,v}$, where w and l are the width and length of the discontinuity. Under the assumption that both width and length scale with thickness d (Zhdankin et al., 2013), this simplifies to $A_{eff} \sim d^2 \sin \theta_{n,v}$. Normalizing this by the area of the spherical shell, $4\pi r^2$, gives the fractional coverage. Consequently, the global occurrence rate f_{global} is proportional to the local (spacecraft-measured) rate f_{local} , scaled by the inverse of this fractional area: $f_{global} \propto f_{local} / (\bar{d}^2 \sin \bar{\theta}_{n,v} / r^2)$ where $\bar{d}$ and $\bar{\theta}_{n,v}$ are the average values of d and $\theta_{n,v}$ at that radial distance. Accounting for this geometric effect significantly reduces the apparent discrepancy in global occurrence rates between 1 AU (e.g., Wind) and 5 AU (e.g., Juno) - from 5 : 1 to 1.3 : 1. The residual difference likely results from additional physical processes, such as discontinuity annihilation through mechanisms like magnetic reconnection during solar wind propagation. Future modeling efforts of SWD generation and evolution should therefore incorporate both geometric and physical factors to fully capture the observed trends.

It is worth noting that our findings on the radial variation of the occurrence rate are qualitatively consistent with the trends observed in the inner heliosphere, for example $f_{local} \propto 1/r^2$ in Liu et al. (2021) and $f_{local} \propto 1/r^{1.3}$ in Söding et al. (2001). While these scalings are steeper than that derived here, the difference may arise from several factors. First, the identification criteria and detection thresholds differ across studies, potentially influencing the inferred occurrence rates. Second, the dominant magnetic field component transitions from B_r in the inner heliosphere (where $B_r \propto 1/r^2$) to B_ϕ in the outer heliosphere (where $B_\phi \propto 1/r$), leading to different geometric projection effects through $\sin \theta_{n,v}$. In addition, the different scaling with radial distance for rotational and tangential discontinuities reported in Liu et al. (2021) may reflect differences in their orientation and its evolution with radial distance, which in turn affects the geometric factor and the resulting observed scaling.

2.4 Conclusion

We have collected 5 years of solar wind discontinuity data from Juno, Wind, THEMIS-B, and STEREO-A. The results of our analysis can be summarized as follows:

- The occurrence rate (normalized to that at 1 AU) of SWDs decreases with radial distance from the Sun, following a $1/r$ law within $[1, 5]$ AU.
- The thickness of SWDs increases with radial distance from the Sun; however, after normalization to ion inertial length, the thickness slightly decreases or remains almost constant within the 1-sigma spread of the distribution. The thickness distribution remains almost constant over a one-year observation period.
- The current density of SWDs decreases with radial distance from the Sun, but after normalization to the Alfvén current, it slightly increases or remains almost constant well within the 1-sigma spread of the distribution. The current density distribution slightly increases from 2011 to 2016, but after normalization, it remains identical across the five years, indicating that there is no effect of long-term (i.e., solar cycle) temporal variations on the normalized current density.

These findings provide key observational constraints for future models of SWD generation, evolution, and dissipation, and—together with the inner heliosphere results of Chapter 3—supply the empirical foundation for the particle scattering and transport analyses developed in Chapter 4 and Chapter 5. Our study advances previous research by systematically characterizing SWD properties across a broad range of radial distances, using a single spacecraft (Juno) and validating the results through consistent comparisons with multi-spacecraft observations at 1 AU. By revealing consistent normalization behaviors (such as thickness and current density relative to ion inertial length and Alfvén current, respectively), we clarify the evolutionary trends of SWDs in the heliosphere. We conclude that the majority of SWDs likely originate close to the Sun and subsequently evolve dynamically as they propagate outward, with their persistence and structure strongly influenced by both geometric spreading and physical dissipation processes. These insights improve our understanding of the origins of SWD and their influence on the dynamics of solar wind, offering a robust framework for future theoretical and observational studies.

2.5 Supplementary Material

This supplementary material includes Figure 2.9, which compares solar wind properties between model predictions and JADE observations. It also contrasts discontinuity prop-

erties derived using normal directions obtained from the cross-product method and the minimum variance analysis (MVA). In addition, Figure 2.10 evaluates the sensitivity of our SWD detection method across a wide range of radial distances r , by analyzing newly identified discontinuities for various values of the temporal parameter T , ranging from 20 to 60 seconds. The figure highlights how the relative percentage of detected discontinuities varies with radial distance for each T .

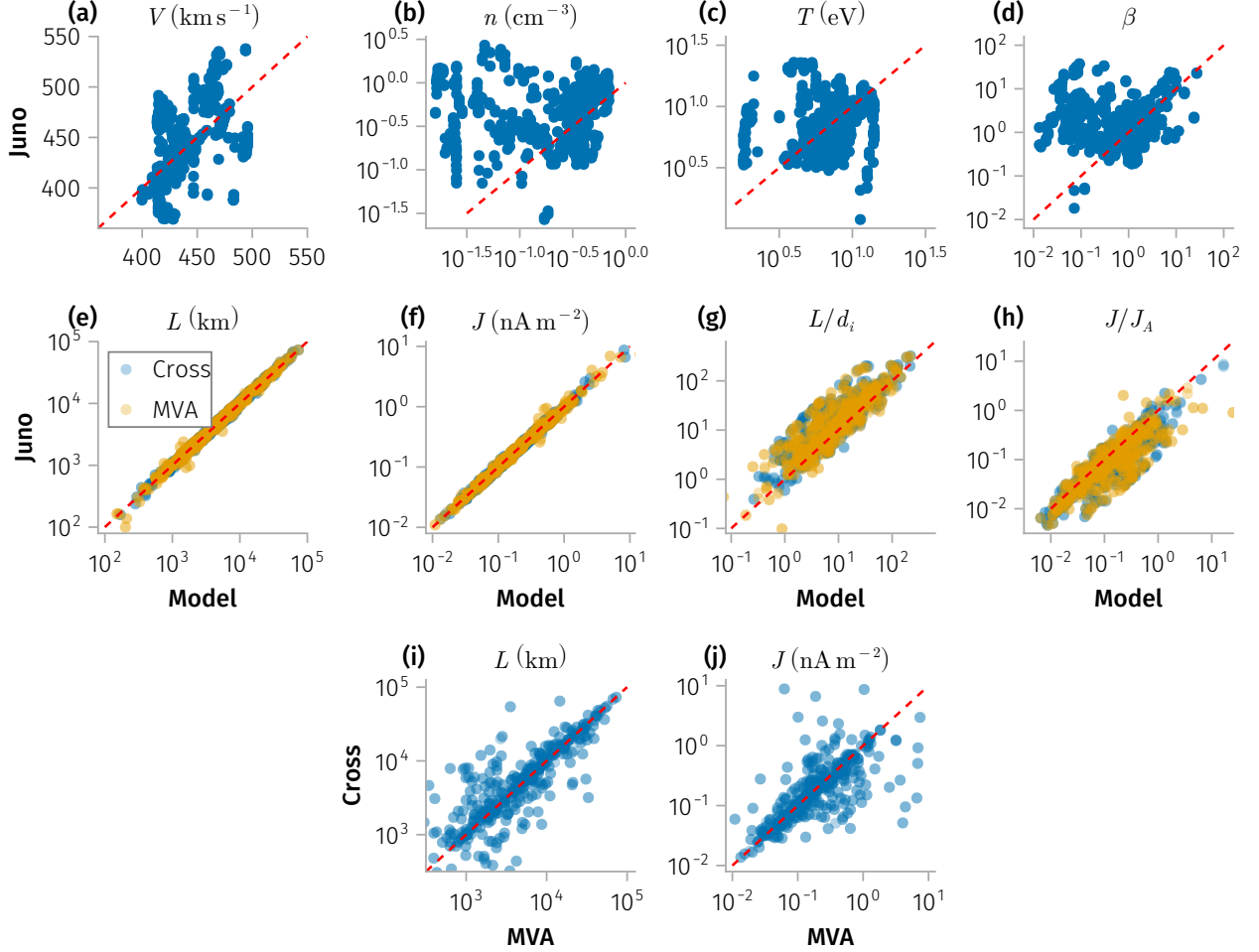


Figure 2.9: (a-d) Comparison of solar wind properties between the model (x-axis) and JADE observations (y-axis): velocity (a), density (b), temperature (c), and plasma beta (d). (e-h) Comparison of discontinuity properties between the model and JADE observations: thickness (e), current density (f), normalized thickness (g), and normalized current density (h). The blue dots represent values derived using the cross-product normal method, while the yellow dots correspond to those obtained using the minimum variance analysis (MVA). (i-j) Scatter plots directly comparing discontinuity thickness (i) and current density (j), with values from the cross-product method on the y-axis and those from MVA on the x-axis.

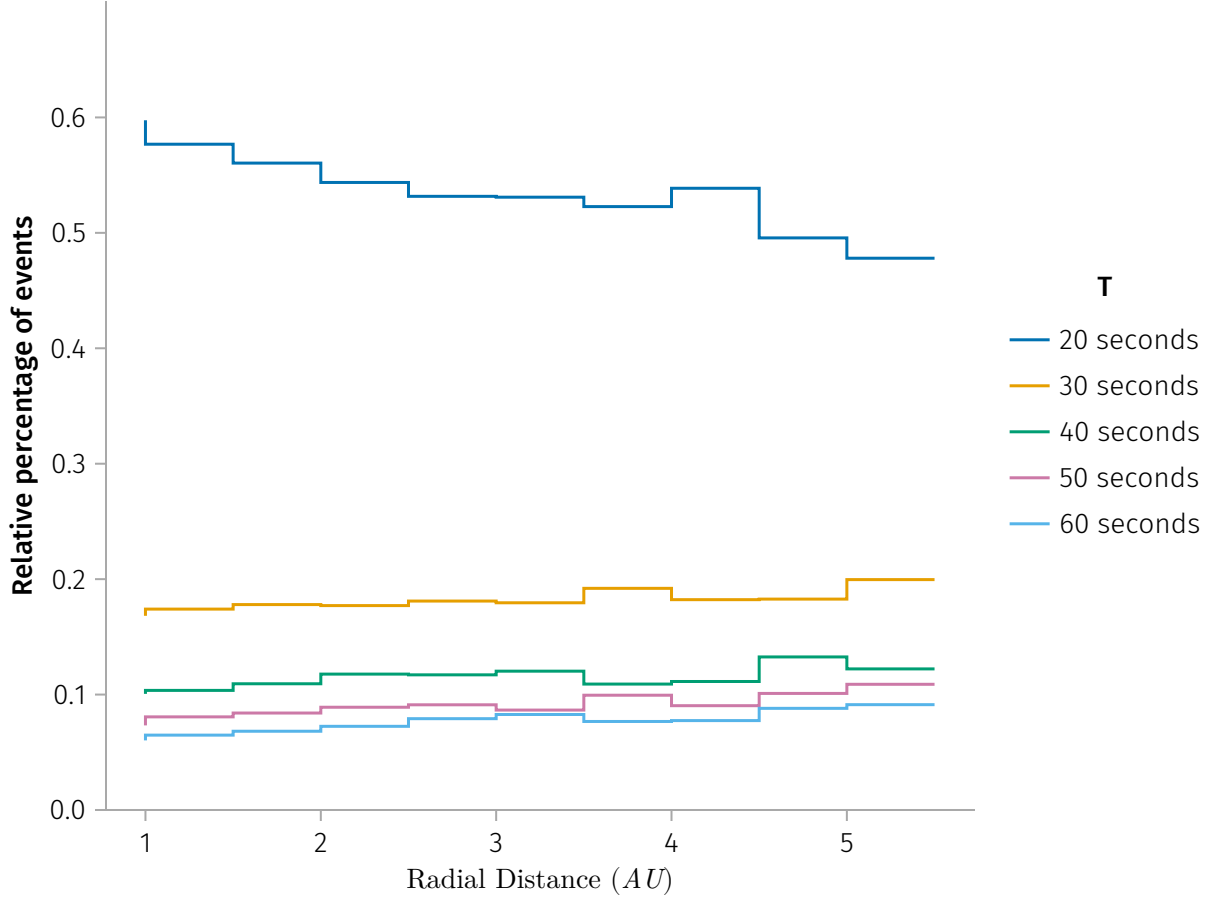


Figure 2.10: The relative percentage of events as a function of radial distance (in AU) for different values of the parameter T (20s, 30s, 40s, 50s, and 60s). At a given radial distance, we remove duplicate discontinuities identified across multiple datasets with different values of the parameter T . Specifically, discontinuities identified at lower T values are excluded from datasets with higher T values. Subsequently, we calculate the relative percentage of discontinuities, normalized to the total number of discontinuities identified across all T values.

Chapter 3

Comparison of Solar Wind Current Sheets in the Inner Heliosphere

Current sheets are ubiquitous mesoscale structures in the solar wind, where the magnetic field changes direction abruptly over ion-scale thicknesses; whereas their lateral extents can exceed typical magnetohydrodynamic (MHD) scales (Zhdankin et al., 2013). They are most readily identified by sharp magnetic-field rotations, but can also be evident in simultaneous changes of plasma density, bulk velocity, and temperature (Colburn & Sonett, 1966; Shen, 2024; Söding et al., 2001). As signatures of intermittency in turbulent solar wind, current sheets concentrate energy dissipation across scales and are important sites of plasma heating and particle acceleration (Borovsky, 2010; Osman et al., 2012; Tessein et al., 2013).

Understanding the formation, structure, and evolution of current sheets at different heliocentric distances is crucial for elucidating the mechanisms that govern solar wind turbulence and heating. Several statistical studies have investigated the properties of solar wind current sheets over a wide range of radial distances (Artemyev et al., 2018; Liu et al., 2021; Lotekar et al., 2022; Mariani et al., 1983; Perrone et al., 2020; Vasko et al., 2022; 2024). Despite this progress, several important gaps remain. First, many earlier studies rely on datasets obtained at different times and different distances with varying temporal resolution of magnetic field measurements, which complicates consistent comparisons across heliocentric distances. Few investigations have examined simultaneous observations from multiple radial positions (Telloni, 2023; Velli et al., 2020), limiting our understanding of how the properties of current sheets evolve as the solar wind expands. Second, existing current sheet identification methods often depend on fixed thresholds—such as absolute magnetic-field jumps—or are highly sensitive to data resolution, as in the case with partial variance increment techniques (Greco et al., 2017). To enable meaningful cross-mission comparisons, more robust approaches based on normalized, resolution-independent criteria are needed. Finally, most prior work has classified discontinuities within the ideal MHD framework—for instance, distinguishing between tangential and rotational discontinuities

(Madar et al., 2024; Neugebauer, 2006). While useful in some contexts and extensively studied, these categories become inadequate at ion scales, where kinetic and multi-fluid effects play a central role. In this study, we move beyond strict, ideal, and single-fluid MHD classifications and explore the Alfvénic character of current sheets—that is, the extent to which plasma and magnetic-field variations follow Alfvénic correlations (Shen et al., 2024). Although this perspective is fundamental for understanding the origin and evolution of current sheets, it has received relatively limited attention in prior studies.

The Parker Solar Probe (PSP) mission (Fox et al., 2016) offers an unprecedented opportunity to probe current sheets in the near-Sun environment with high cadence and to compare these observations with near-Earth measurements. In this study, we focus on three PSP perihelion intervals (Encounters 7–9) selected for their differing geometric alignments with the near-Earth spacecraft ARTEMIS and WIND. Encounter 7 features strong radial alignment that enables sampling of similar solar wind streams, while Encounter 8 exhibits weaker alignment, and Encounter 9 places PSP roughly 180° away in longitude. These contrasting configurations enable a controlled examination of current sheet properties and, more broadly, provide insight into how those properties depend on the solar wind’s source region.

Using a robust automated detection algorithm, we identify and analyze more than 45,000 current sheets across the three selected intervals (approximately 17,000 from PSP). We systematically characterize their rotation profiles, thicknesses, current densities, magnetic field jumps, and Alfvénic properties. Combined with the outer heliosphere survey of Chapter 2, these results establish the empirical foundation for the particle scattering and transport models developed in Chapter 4 and Chapter 5. The remainder of this paper is organized as follows: Section 2 describes the datasets and analysis methods; Section 3 presents the results and discusses their physical implications; and Section 4 summarizes the main conclusions.

3.1 Dataset and Methods

In this study, we utilize magnetic field and plasma measurements from PSP (Fox et al., 2016), ARTEMIS (Angelopoulos, 2011), and WIND (Acuña et al., 1995). For PSP, high-resolution magnetic field data are obtained from the FIELDS instrument (Bale et al., 2016), with a time cadence of up to 3.4 ms. Plasma measurements are provided by the Solar Wind Electrons, Alphas, and Protons (SWEAP) suite (Kasper et al., 2016), with a typical cadence of 1.7 s for ion moments from the Solar Probe ANalyzer for Ions (SPAN-I). Proton and electron temperature anisotropies are derived from measurements by the Solar Probe ANalyzer for Ions (SPAN-I) and Electrons (SPAN-E) electrostatic analyzers (Livi et al., 2022; Whittlesey et al., 2020). For ARTEMIS, we use magnetic-field measurements from the Fluxgate Magnetometer sampled at approximately 16 samples per second (Auster et al., 2008), along with plasma velocity and density measurements from the Electrostatic Analyzer (ESA) instrument, which provides moments at a cadence of 4 s (McFadden et al., 2009). For WIND, we use magnetic-field data from the Magnetic Field Investigation (MFI) instrument sampled at 11 samples per second (Lepping et al., 1995), together with ion (proton and alpha-particle) moments from the ion electrostatic analyzers (PESA) of the Plasma Analyzer (3DP), measured at a cadence of approximately 3.1 seconds (Lin et al., 1995).

It is worth noting that for PSP, although ion data is also available from SPC, the SPAN-i data was chosen due to its higher temporal resolution. Plasma density estimates delivered by the quasi-thermal noise spectroscopy (QTN) are also available (Moncuquet et al., 2020). We generally find that the results using QTN data do not differ significantly from those derived from SPAN-I data. Due to the limitations of SPAN-I data during the early mission phases, when a significant portion of the solar wind distributions was out of the instrument’s view, our study concentrates on data beginning with Encounter 7, where SPAN-I provides more accurate measurements.

Our study investigates the evolution of current sheet properties during the radial expansion of the solar wind. To distinguish between spatial and temporal variations, we analyze three distinct time intervals corresponding to PSP Encounters 7 through 9, each characterized by different PSP–Earth alignments (Telloni, 2023; Velli et al., 2020). Encounter 7 features a favorable alignment between PSP and Earth, enabling nearly simultaneous multi-point observations (PSP approached perihelion on 2021-01-17 17:40; data intervals

are 2021-01-15 – 2021-01-20 for PSP and 2021-01-17 – 2021-01-25 for ARTEMIS and WIND). Encounter 8 exhibits moderate alignment (PSP perihelion at 2021-04-29 08:48; data intervals 2021-04-27 – 2021-05-02 for PSP and 2021-04-29 – 2021-05-04 for ARTEMIS and WIND). In Encounter 9, PSP and Earth are located at substantially different helio-longitudes, with most PSP footpoints lying on the far side of the Sun (PSP perihelion on 2021-08-09 at 19:11; data intervals 2021-08-07 – 2021-08-12 for PSP and 2021-08-09 – 2021-08-14 for ARTEMIS and WIND). By comparing these intervals, we assess how the derived current sheet properties depend on the relative geometry of the heliospheric magnetic field and the temporal context of the observations. Our results show that although specific plasma parameters vary slightly among intervals, the overall statistical characteristics of the current sheets remain largely consistent. This suggests that the observed statistics are not strongly sensitive to either the relative geometry or the temporal context of the measurements.

Figure 3.1 provides an overview of the selected time interval from Encounter 7, comparing measurements from the PSP (left panels) and WIND (right panels) missions. From top to bottom, the panels display 8-minute averages of the magnetic field magnitude, proton number density, and proton bulk flow speed, followed by ion and electron temperatures resolved in the parallel and perpendicular directions. To facilitate comparison, WIND measurements are scaled to $20R_{\odot}$ using the empirical relations for the magnetic-field magnitude B and plasma number density n : $B_{\text{scaled}}/B = (20R_{\odot}/1 \text{ AU})^{-1.59}$, $n_{\text{scaled}}/n = (20R_{\odot}/1 \text{ AU})^{-1.96}$ (Perrone et al., 2019). The fifth and sixth panels present, respectively, the median Alfvén ratio and the total number of current sheets identified within each four-hour interval. The Alfvén ratio is defined as $R_{VB} = |\Delta \mathbf{V}| / |\Delta \mathbf{V}_A|$, where $\mathbf{V}$ is the plasma velocity and $\mathbf{V}_A = \mathbf{B}/\sqrt{\mu_0 \rho}$ is the Alfvén velocity, with ρ the mass density and μ_0 the vacuum permeability. Including the anisotropy factor $\Lambda = \mu_0(p_{\parallel,e} - p_{\perp,e} + p_{\parallel,i} - p_{\perp,i})/B^2$ does not significantly affect the Alfvén ratio $R_{VB}^* = R_{VB}/\sqrt{1 - \Lambda}$, where $p_{\parallel}$ and $p_{\perp}$ denote the pressures parallel and perpendicular to the magnetic field for electrons (e) and ions (i); its average value is approximately 0.5 for PSP and 0.4 for WIND over the entire time interval. The number of current sheets varies from roughly 100 to 300 per four-hour window, corresponding to an average of about 1,000 and 800 current sheets per day for PSP and WIND, respectively. The PSP occurrence rates are broadly consistent with those of previous studies at similar heliocentric distances (Liu et al., 2021; Lotekar et al.,

2022). Compared with the occurrence rate of about 150 events per day identified at 1 AU by Vasko et al. (2022); Zhang et al. (2025a), our analysis detects substantially more current sheets, mainly because we do not limit our survey to only the most intense kinetic-scale current sheets (see Methodology below).

Panels (a.7) and (b.7) present the time series of cross helicity and residual energy, calculated every 8 minutes for PSP and WIND, respectively. These quantities characterize the Alfvénic nature of and energy balance between the ambient plasma flow and magnetic fluctuations, and are computed in the standard form (Huang et al., 2025; Wicks et al., 2013): $\sigma_c = \frac{2\langle\delta\mathbf{V}\cdot\delta\mathbf{V}_A\rangle}{\langle\delta\mathbf{V}^2\rangle+\langle\delta\mathbf{V}_A^2\rangle}$, $\sigma_r = \frac{\langle\delta\mathbf{V}^2\rangle-\langle\delta\mathbf{V}_A^2\rangle}{\langle\delta\mathbf{V}^2\rangle+\langle\delta\mathbf{V}_A^2\rangle}$, where $\delta\mathbf{V}$ and $\delta\mathbf{V}_A$ are the fluctuating velocity and Alfvén velocity, respectively. Alfvénic fluctuations are typically characterized by $|\sigma_c| \approx 1$ and $|\sigma_r| \approx 0$. A large magnitude of the normalized cross-helicity, σ_c , indicates that the fluctuations are dominated by either outward- or inward-propagating Alfvénic modes, while a small magnitude of the normalized residual energy, σ_r , implies near-equipartition between kinetic and magnetic fluctuation energies. For PSP, σ_c displays extended intervals with values close to ± 1 , signifying prolonged periods of strongly Alfvénic fluctuations. Notably, a sharp transition in σ_c occurs around 12:00 on 2021-01-17, coincident with a heliospheric current sheet crossing. The residual energy σ_r remains mostly negative throughout, consistent with magnetic-energy-dominated turbulence (McIntyre et al., 2023; Sioulas et al., 2023). In contrast, both σ_c and σ_r measured by WIND fluctuate more irregularly and lack the long, coherent intervals of high Alfvénicity seen by PSP. The cross helicity varies broadly between -0.5 and $+0.5$, reflecting the more evolved and mixed solar wind at 1 AU where Alfvénic correlations weaken due to turbulence evolution and stream interactions. The final two panels display 8-minute averages of helium abundance and plasma beta, providing complementary information on the compositional and thermal conditions of the solar wind. The helium abundance is sensitive to the coronal heat flux into the chromosphere and transition region, with local variations in magnetic topology modulating how this heat flux is transported and ultimately imprinting source-region signatures in the solar wind (Alterman & D’Amicis, 2025). Plasma beta, which measures the ratio of thermal to magnetic pressure, is typically enhanced in slow solar wind originating from the streamer belt, forming a high- β equatorial plasma sheet in the vicinity of heliospheric current sheet crossings (Huang et al., 2023). Together, these parameters provide critical diagnostics for identifying the source regions of different solar wind streams.

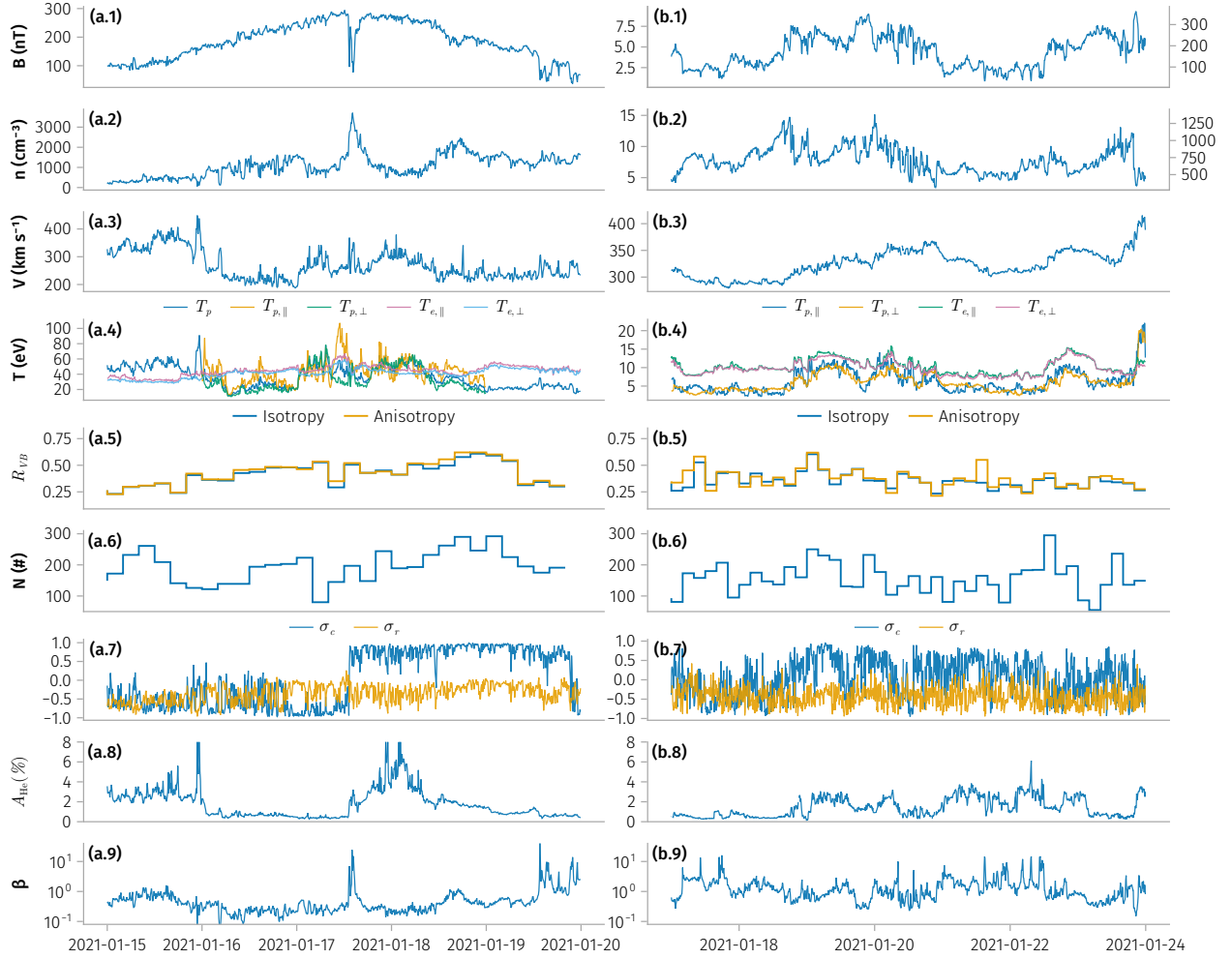


Figure 3.1: Overview of Encounter 7 comparing PSP (left) and WIND (right) observations. Panels show 8-minute averages of (a.1, b.1) magnetic field magnitude, (a.2, b.2) proton density, (a.3, b.3) flow speed, (a.4, b.4) ion and electron temperatures, (a.5, b.5) Alfvén ratio, (a.6, b.6) current-sheet counts, (a.7, b.7) cross helicity and residual energy, (a.8, b.8) helium abundance, and (a.9, b.9) plasma beta. WIND measurements are radially scaled to $20R_{\odot}$ for comparison.

To identify current sheets, we employ an improved automated detection algorithm adapted from previous studies (Liu et al., 2022b; Zhang et al., 2025a). The magnetic field data are divided into consecutive time intervals, each lagged by a time T . For each interval, we compute the standard deviation of the vector magnetic field, $\sigma(\mathbf{B})$, and compare it with those of the adjacent intervals, $\sigma(\mathbf{B}_{-})$ and $\sigma(\mathbf{B}_{+})$. An interval is flagged as a potential current sheet when its standard deviation significantly exceeds those of its neighbors, indicating a sharp magnetic field variation: $\sigma(\mathbf{B}) > 2 \max(\sigma(\mathbf{B}_{-}), \sigma(\mathbf{B}_{+}))$. For each candidate interval, we refine the boundaries of the potential current sheet by using the distance

between two magnetic field vectors, $d(t_a, t_b) = \| \mathbf{B}(t_a) - \mathbf{B}(t_b) \|$. The leading and trailing edges, t_a and t_b ($t_a < t_b$), are defined such that $d(t_a, t_b)$ attains its maximum value within the interval. To minimize false detections—particularly those caused by wave-like or hole-like structures (Karlsson et al., 2021) that may mimic current sheet signatures—we impose the additional requirement $\| \Delta \mathbf{B} \| / \langle \| \mathbf{B} \| \rangle \geq 1/10$, where $\langle \| \mathbf{B} \| \rangle$ is the mean magnetic-field magnitude averaged over the duration of the current sheet crossing. We also evaluate the magnetic field orientation across each candidate structure by computing the angles between magnetic field vectors at the leading and trailing edges and comparing them with the angles between each edge and the midpoint of the interval. Only intervals where the edge-to-edge angle exceeds all interior angles are retained as valid current sheet candidates. Because current sheets span a range of spatial and temporal scales, we performed the identification procedure using multiple time lags ($T = 2, 4, 8, 16, 32, 64$ s). The resulting event lists from each search were merged into a comprehensive catalog after duplicates were removed. A subset of automatically detected intervals was visually inspected. All visually inspected events show clear current sheet signatures, such as (1) well-bounded regions with localized rotations of the magnetic field vector and (2) magnetic reversals in the maximum-variance direction. These features confirm the robustness and reliability of the automated detection procedure.

We also compared our approach to the Partial Variance of Increments (PVI) method for current sheet identification (Greco et al., 2017). Although the PVI technique is effective for detecting short-duration, kinetic-scale current sheets characterized by sharp gradients, it often fails to capture larger-scale structures that exhibit smoother yet coherent magnetic field variations. Moreover, the PVI method is highly sensitive to data resolution, complicating comparisons across missions with instruments of different temporal cadences. When the analysis is restricted to the smallest lag available in all datasets (e.g., $T = 2$ s), the PVI method identifies a comparable number of current sheets and produces similar statistical properties to our standard detection approach. However, because PVI does not reliably capture the full range of larger-scale events and is difficult to apply uniformly across missions, we do not proceed to utilize PVI-derived detections.

Once the current sheets are identified, we apply a minimum variance analysis (MVA) (Sonnerup & Scheible, 1998) to transform the magnetic field and plasma data into the local

LMN coordinate system, where L , M , and N correspond to the directions of maximum, intermediate, and minimum variance, respectively. The maximum variance component, B_L , is then fitted with a hyperbolic tangent profile to extract parameters characterizing each current sheet, following the standard Harris current sheet model (Harris, 1962): $B_L(t) = B_{L,i} \tanh\left(\frac{t-t_i}{\Delta t_i/2}\right) + c_i$ where $B_{L,i}$ is the magnitude of the magnetic field change in the maximum variance direction, t_i is the detection time, Δt_i is the temporal duration, and c_i is a magnetic field offset.

Assuming that the current sheets are one-dimensional planar structures, their spatial scale (thickness) can be estimated once the normal direction is determined. The normal vector can be obtained either from the minimum variance direction given by MVA or from the cross product of the magnetic field vectors at the current sheet boundaries. However, previous studies have shown that the MVA-derived normal direction can often be unreliable (Knetter et al., 2004; Wang et al., 2024). The accuracy can be improved by imposing additional constraints such as $\Delta|B|/|B| > 0.05$ or $\omega > 60^\circ$ (Liu et al., 2023), where $\Delta|B|$ denotes the change in magnetic field magnitude and ω is the field rotation angle across the discontinuity. The cross-product method, on the other hand, requires that the magnetic field component along the normal direction (B_n) be small, making it unsuitable when B_n is large. In this study, we apply both methods and report results based on the subset of events that satisfy $\Delta|B|/|B| > 0.05$ or $\omega > 60^\circ$. The results derived using the cross-product method are presented in the Supplementary Material.

The spatial thickness of each current sheet is estimated as $\delta = V_n \Delta t$, where V_n is the plasma velocity projected along the normal direction. The current density associated with the main magnetic field reversal is calculated from $J_m = -\frac{1}{\mu_0 V_n} \frac{dB_L}{dt}$. Within our fitting framework, the magnetic field derivative can be approximated as $\max(dB_L/dt) = 2B_{L,i}/\Delta t_i$. This approach provides a more robust estimate than direct differentiation, as it is less sensitive to measurement noise and limited temporal resolution. The mean values of proton density, temperature, and alpha-particle density of each interval are used to compute the Alfvén velocity, pressure anisotropy factor, plasma beta, and alpha-particle abundance, thereby providing a comprehensive characterization of the plasma environment associated with each current sheet.

The upstream and downstream conditions are defined using timestamps immediately before and after the current sheet boundaries, respectively, such that $\Delta \mathbf{V} = \mathbf{V}_{\text{downstream}} - \mathbf{V}_{\text{upstream}}$. The cosine of the angle between the velocity jump, $\Delta \mathbf{V}$, and the Alfvén velocity jump, $\Delta \mathbf{V}_A$, is then calculated as $\cos \theta = \frac{\Delta \mathbf{V} \cdot \Delta \mathbf{V}_A}{\|\Delta \mathbf{V}\| \|\Delta \mathbf{V}_A\|}$, serving as a measure of Alfvénic alignment. Finally, the cross helicity, σ_c , and residual energy, σ_r , are computed within intervals extending from each current sheet edge to eight times the current sheet duration (or at least 30 s on either side). These parameters quantify the degree of Alfvénicity and the relative contributions of kinetic and magnetic energy fluctuations in the ambient solar wind.

Figure 3.2 presents two representative current sheet examples observed by PSP (left panels) and ARTEMIS (right panels). From top to bottom, the panels display, in LMN coordinates, the magnetic field, proton velocity, and the shifted Alfvén velocity $\mathbf{V}_A = \frac{\mathbf{B}}{\sqrt{\mu_0 \rho}} - \mathbf{V}_{A,0}$, where $\mathbf{V}_{A,0}$ is the Alfvén velocity at the center of the current sheet. The cosine of the angle between the velocity jump, $\Delta \mathbf{V}$, and the Alfvén velocity jump, $\Delta \mathbf{V}_A$, is approximately -0.82 for PSP and -0.95 for ARTEMIS, indicating strong anti-correlation. The corresponding Alfvén ratio, R_{VB} , is approximately 0.32 for both PSP and ARTEMIS.

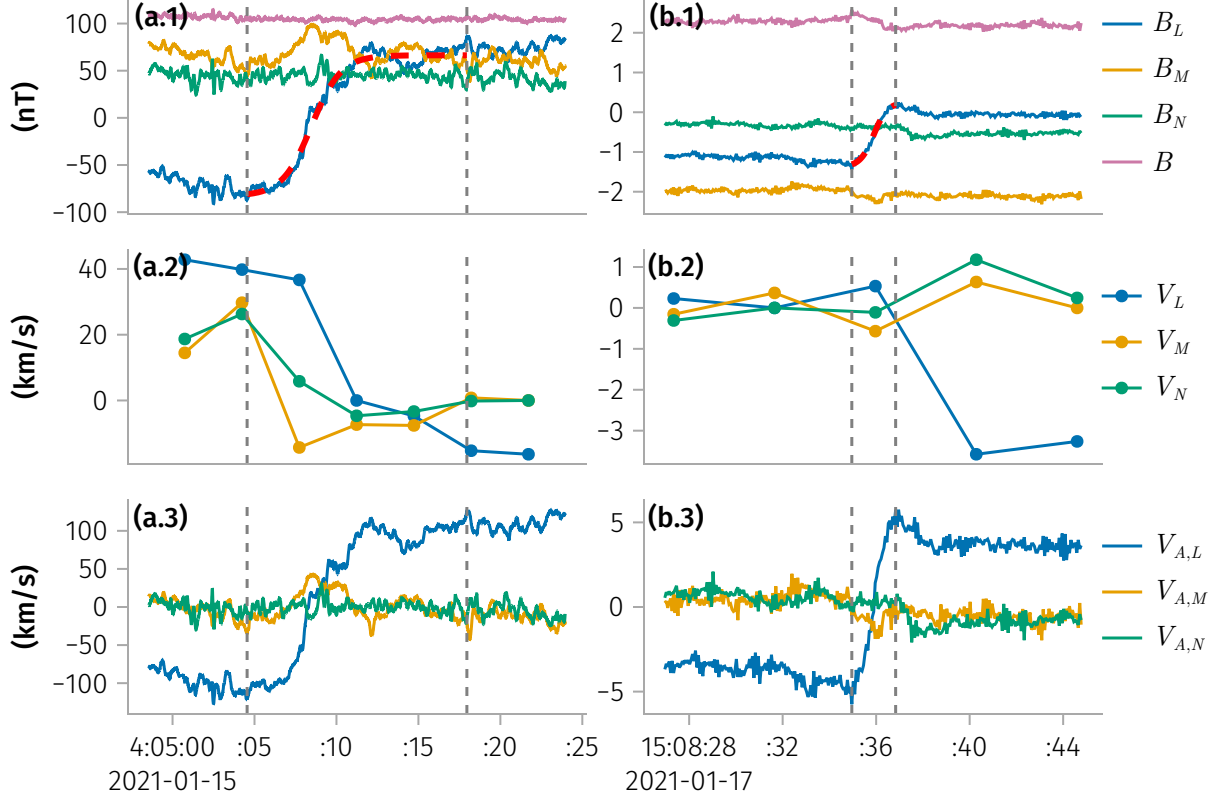


Figure 3.2: Representative examples of current sheets observed by the Parker Solar Probe (PSP; panels a.1–a.3) and ARTEMIS (panels b.1–b.3) in the local LMN coordinate system. Panels (a.1) and (b.1) show the magnetic field components B_L , B_M , and B_N , together with the magnetic field magnitude B . The red dashed lines indicate the hyperbolic tangent fits used to derive current sheet parameters. Panels (a.2) and (b.2) display the proton bulk velocity components V_L , V_M , and V_N . Panels (a.3) and (b.3) show the shifted Alfvén velocity components $V_{A,L}$, $V_{A,M}$, and $V_{A,N}$. The vertical gray dashed lines mark the leading and trailing edges of each identified current sheet.

3.2 Results and Discussion

Figure 3.3 presents the probability density functions (PDFs) of current sheet thickness, δ , current density, J , and magnetic field jump magnitude, $|\Delta \mathbf{B}|$, derived from different missions and time intervals. For thickness and current density, we display here a subset of the dataset where MVA normals are trustworthy. The results using the cross product method for the current sheet normals are displayed in Supplementary Material **Figure 3.9** and do not show any significant difference. Note, we do not restrict the dataset for the statistics of magnetic field jump magnitude since the jump magnitude does not depend on

the normal direction. To better understand how these properties relate to the local plasma environment (Vasko et al., 2022; 2024; Zhang et al., 2025a), we normalize the current sheet thickness by the ion (proton) inertial length, $d_i = c/\omega_{pi}$, and the current density by the Alfvén current density, $J_A = eNV_A = B/\mu_0 d_i$. Both parameters represent natural plasma scales: the ion inertial length characterizes the spatial scale where ions decouple from the magnetic field, while the Alfvén current density corresponds to the characteristic current generated by the drift of electrons and ions relative to each other at the local Alfvén speed, V_A . These quantities are particularly relevant in studies of MHD turbulence and magnetic reconnection (Franci et al., 2017; Zhdankin et al., 2013).

The absolute thickness, δ , increases from PSP to ARTEMIS and WIND, indicating a broadening of current sheets with solar wind expansion. After normalization by the ion inertial length, however, the characteristic scale δ/d_i decreases slightly with increasing distance. Similar behavior has been reported by Madar et al. (2024) using Parker Solar Probe and Solar Orbiter data, where the thickness of rotational discontinuities in ion inertial length units decreases rapidly until approximately 0.3 AU. We additionally examined the scaling proposed by Shaikh et al. (2026), which accounts for the dependence of current sheet thickness on plasma beta. Applying the proton-beta-dependent normalization, $\delta/d_i \beta^{0.23}$, does not appreciably modify the distributions of normalized thicknesses shown in Figure 3.3, indicating that proton beta effects do not play a dominant role in shaping the observed radial trends in our dataset.

The normalized current density, J_m/J_A , shows remarkably similar distributions across the PSP, WIND, and ARTEMIS datasets. This suggests that the relative strength of current sheets, when expressed in local plasma units, is largely independent of radial distance from the Sun. This trend is consistent with previous studies based on joint WIND–Ulysses measurements between 1 and 5 AU (Vasko et al., 2022; 2024) and Juno observations from 1–5 AU (Zhang et al., 2025a). All of which similarly found that the normalized current density remains nearly constant while the normalized thickness gradually decreases with increasing heliocentric distance.

The distributions of magnetic field jumps ($|\Delta \mathbf{B}|$ and $|\Delta \mathbf{B}|/|\mathbf{B}|$) exhibit pronounced differences across the missions. In particular, PSP observations display a markedly distinct

distribution compared with WIND and ARTEMIS, characterized by substantially larger magnetic field jumps, even after normalization. These enhanced jumps indicate stronger magnetic field reversals in the near-Sun environment and are likely associated with the frequent occurrence of switchbacks (Bale et al., 2019; Wit et al., 2020). Previous studies have shown that switchbacks progressively dissipate with increasing heliocentric distance, as their amplitudes decrease more rapidly than the background turbulent fluctuations (Shi et al., 2022; Soni et al., 2024; Tenerani et al., 2021). The discrepancy between ARTEMIS and WIND is more plausibly related to the ARTEMIS spacecraft’s proximity to the bow shock. The foreshock region hosts strong compressional fluctuations and reflected hot ions, favoring a higher occurrence of compressional current sheets compared to the pristine solar wind. This environmental effect likely contributes to the larger (normalized) magnetic-field jumps observed by ARTEMIS (Kropotina et al., 2021).

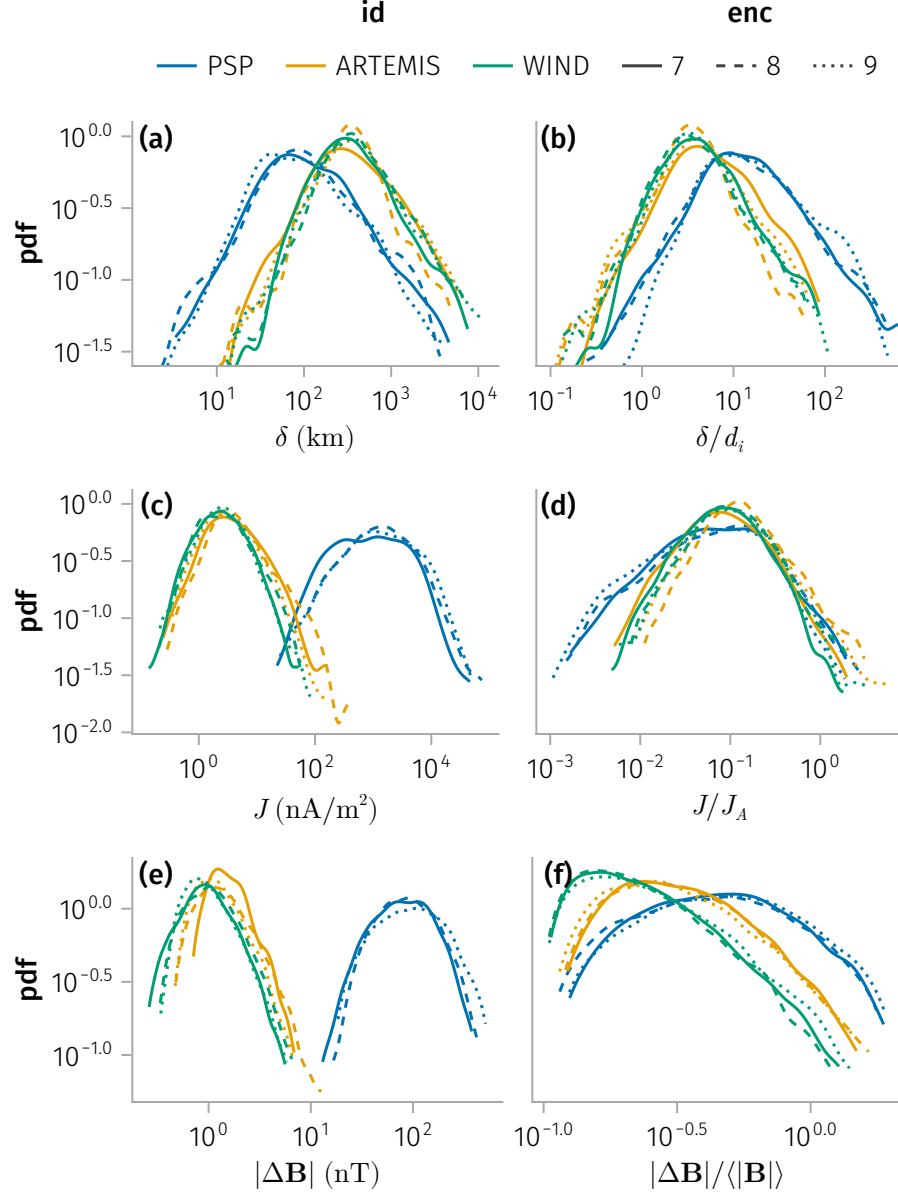


Figure 3.3: Probability density functions of current sheet properties obtained from different missions (color-coded) and encounters (distinguished by line styles). The left column shows unnormalized quantities, while the right column presents values normalized by characteristic plasma scales. From top to bottom, panels display the distributions of (a-b) current sheet thickness δ and its normalized form δ/d_i ; (c-d) current density J_m and normalized current density J_m/J_A ; and (e-f) magnetic field jump magnitude $|\Delta \mathbf{B}|$ and its normalized value $|\Delta \mathbf{B}|/|\langle \mathbf{B} \rangle|$. The ion inertial length is $d_i = c/\omega_{pi}$, and the Alfvén current density is

Figure 3.4 presents the joint distributions between (a) current density and current sheet thickness, (b) normalized current density and normalized thickness, (c) normalized thickness and normalized magnetic field jump, and (d) normalized current density and normalized magnetic field jump. A clear inverse correlation is evident between the (nor-

malized) current density and (normalized) current sheet thickness, indicating that stronger currents are generally associated with thinner sheets—that is, smaller-scale current sheets tend to be more intense. After normalization, the scatter distributions of current density versus thickness are highly similar across different missions (different radial distances), both in overall shape and in the range of values. This similarity suggests that the statistical relationship between normalized current density and scale is largely independent of heliocentric distance.

In contrast, the relationship between the magnetic field jump and current sheet thickness, shown in Panel (c), is relatively weak. For a given range of magnetic field jump amplitudes, the corresponding spatial scales exhibit a broad distribution, spanning up to two orders of magnitude. Moreover, Panel (d) showcases there is no clear one-to-one correspondence between the magnetic field jump amplitude and the current density. Scale-dependent properties of current sheets have been reported by several previous studies using PSP, WIND, and Ulysses observations (Lotekar et al., 2022; Vasko et al., 2022; 2024). However, whereas earlier studies primarily focused on kinetic-scale current sheets, our analysis extends this investigation to a broader range of scales—covering nearly two additional orders of magnitude in normalized current density and normalized current sheet thickness.

Results shown in Figure 3.4 remain largely unchanged when the current sheet normal is determined using the magnetic field cross-product method rather than the minimum variance analysis. This consistency across methods confirms that the observed correlations are not strongly affected by the specific approach used to estimate the current sheet geometry.

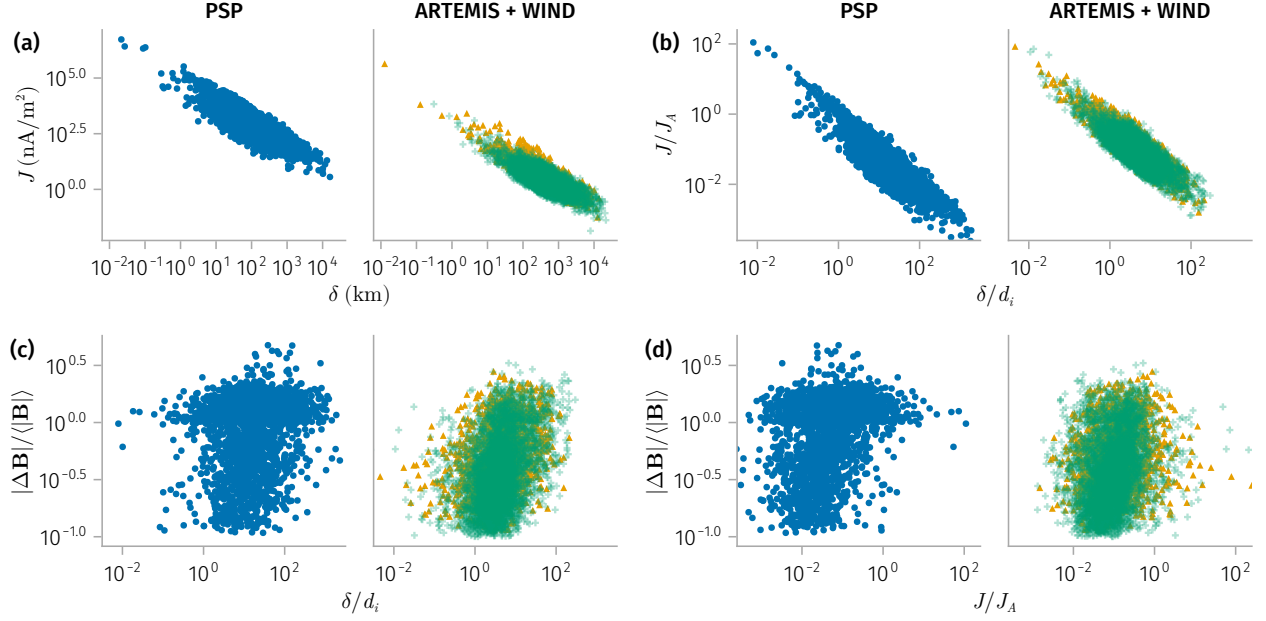


Figure 3.4: Scatter plots of (a) current density versus current sheet thickness, (b) normalized current density versus normalized current sheet thickness, (c) magnetic field jump magnitude versus normalized current sheet thickness, and (d) normalized magnetic field jump magnitude versus normalized current density.

For an ideal MHD rotational discontinuity (RD), variations in the plasma velocity and magnetic field satisfy the Walén relation, $\Delta \mathbf{V} = \pm \Delta \mathbf{V}_A$, and the magnetic field is approximately incompressible across the current sheet, such that $\Delta B \approx 0$ (Hudson, 1970). The Walén relation requires agreement in both magnitude and direction between the plasma velocity change and the corresponding Alfvén velocity change. However, most observed current sheets deviate from these ideal conditions.

To quantify the degree of Alfvénicity and the deviations from ideal RD behavior, we examine both the magnitude and angular differences between $\Delta \mathbf{V}$ and $\Delta \mathbf{V}_A$, as well as the variation in magnetic field strength across each current sheet. Figure 3.5 summarizes the statistical results. Panel (a) shows the ratio of velocity-jump magnitude to Alfvén velocity-jump magnitude. Across all missions, the ratio is generally less than unity, with mean values of approximately 0.6 for PSP and 0.5 for the combined WIND and ARTEMIS datasets. Panel (b) displays the cosine of the angle between the velocity and Alfvén velocity jumps. All missions exhibit clustering near 0° and 180° , corresponding to correlated and anti-correlated states, respectively. PSP observations exhibit stronger alignment (cosine values closer to ± 1), whereas WIND and ARTEMIS data show a broader angular spread.

Panels (c) and (d) present the fractional change in magnetic field magnitude across current sheets. These variations are small (about 0.1 on average) for all missions, with PSP showing slightly smaller changes than WIND and ARTEMIS. This indicates that most current sheets are nearly incompressible.

We also calculate the Alfvén velocity, including the anisotropy factor $\Lambda = \mu(p_{\parallel,e} - p_{\perp,e} + p_{\parallel,i} - p_{\perp,i})/B^2$, for PSP and WIND observations when the necessary plasma data are available. In most cases, including this anisotropy correction does not significantly alter the velocity-jump ratio. The persistent discrepancy between the observed ratios ($R < 1$) and the predictions of anisotropic MHD theory may have several explanations. First, the limited temporal resolution of the plasma anisotropy measurements—typically much lower than that of the magnetic field data—may cause underestimation of instantaneous variations at current sheet crossings (J. Huang et al., 2020; Shen et al., 2024). Second, kinetic-scale magnetic discontinuities often deviate from the assumptions of MHD theory: their non-Maxwellian particle velocity distributions, including plasma agyrotropies and field-aligned beams (Artemyev et al., 2020b; Neukirch et al., 2020a), are not accounted for in the fluid equations but can strongly influence the measured velocity ratios. Finally, uncertainties in deriving the parallel and perpendicular temperatures—typically obtained from nonlinear fits to complex velocity distribution functions—may introduce additional errors, especially when multiple particle populations are present (Halekas et al., 2020; J. Huang et al., 2020).

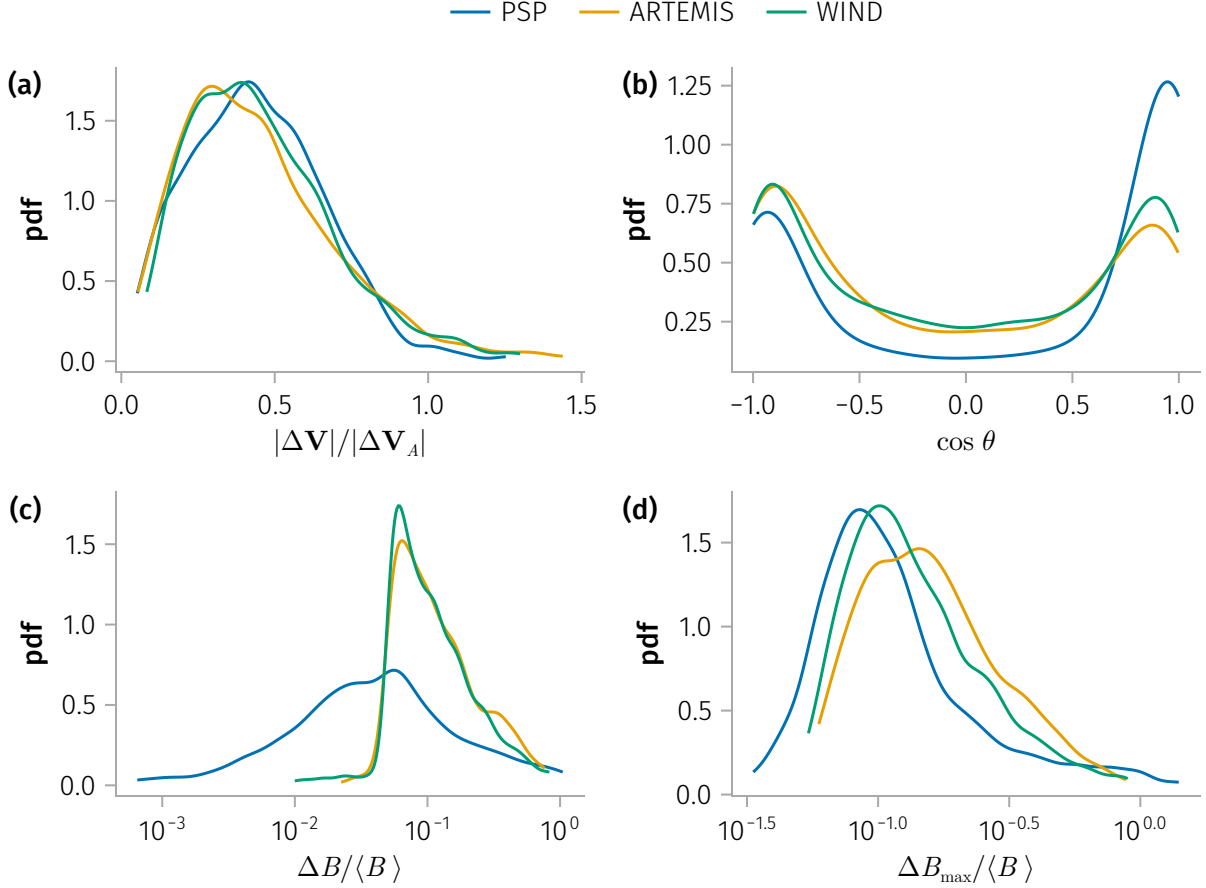


Figure 3.5: Probability density functions of parameters used to characterize the Alfvénicity of current sheets: (a) ratio of velocity-jump magnitude to Alfvén velocity-jump magnitude, (b) cosine of the angle between the two vectors, (c) the variation in magnetic field magnitude between the leading and trailing edges of each current sheet; and (d) the maximum variation in magnetic field magnitude observed within each current sheet.

To further investigate the physical origins of the observed deviations from Alfvénic behavior, we use a single scalar parameter, $Q^\pm$, introduced by (Sonnerup et al., 2018), to quantify the Alfvénicity of current sheets and examine how $Q^\pm$ correlates with key current sheet and plasma parameters.

The parameter $Q^\pm$ is defined as $Q^\pm = \pm \left(1 - \frac{|\Delta \mathbf{V} \mp \Delta \mathbf{V}_A|}{|\Delta \mathbf{V}| + |\Delta \mathbf{V}_A|}\right)$, which combines both magnitude and directional discrepancies between the velocity and Alfvén velocity jumps, and satisfies $-1 < Q^\pm < 1$. The upper sign is used for cases where $\cos \theta > 0$ and the lower sign for $\cos \theta < 0$. The values of $Q^\pm$ approaching ± 1 correspond to a highly Alfvénic behavior. The joint distribution of $|\Delta \mathbf{V}| / |\Delta \mathbf{V}_A|$ and $\cos \theta$ is shown in the first panel of Figure 3.6.

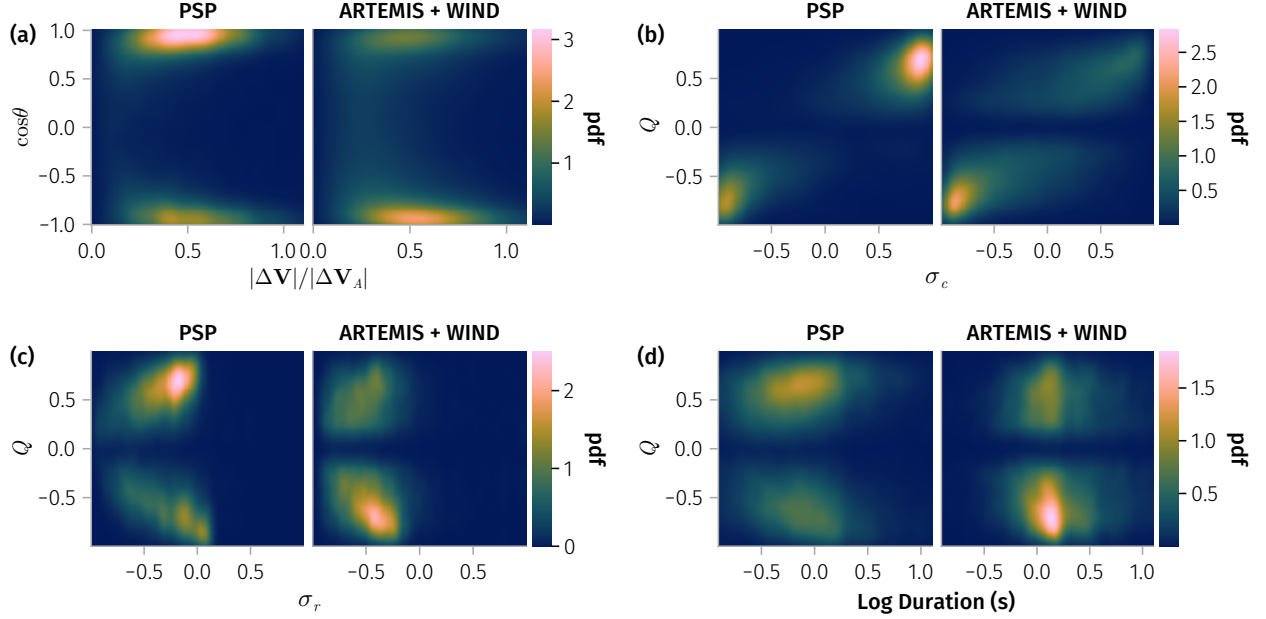


Figure 3.6: (a) Joint distribution of the velocity-jump ratio ($|\Delta \mathbf{V}| / |\Delta \mathbf{V}_A|$) and the cosine of the alignment angle ($\cos \theta$), used in computing the Sonnerup ($Q^\pm$) parameter. (b) Joint distribution of cross helicity σ_c and $Q^\pm$. (c) Joint distribution of residual energy σ_r and $Q^\pm$. (d) Joint distribution of temporal duration and $Q^\pm$.

We examine the relationship between $Q^\pm$ and various current sheet and ambient solar wind properties. Most parameters show little or no correlation with $Q^\pm$; however, two quantities exhibit strong correlations: the cross helicity, σ_c , and residual energy, σ_r , of the surrounding solar wind. These parameters respectively describe the degree of velocity–magnetic field correlation and the partition of energy between velocity and magnetic field fluctuations. Both serve as indicators of the Alfvénic character of the background solar wind rather than of individual current sheets.

Panels (b) and (c) of Figure 3.6 show that the Alfvénicity of the current sheets, represented by Q^+ , increases with greater cross helicity and greater residual energy (more positive), while Q^- increases with greater cross helicity and smaller residual energy (more negative). This trend suggests that current sheets embedded within highly Alfvénic solar wind streams tend to exhibit more substantial velocity–magnetic field alignment, whereas those located in more turbulent or energy-imbalanced regions—where magnetic energy (E_B) exceeds kinetic energy (E_V)—exhibit greater departures from Alfvénic expectations.

Additionally, observations reveal a weak positive correlation between Alfvénicity ($Q^\pm$) and the temporal duration of current sheets, as shown in Panel (d) of Figure 3.6. In contrast, no clear correlation is found between current-sheet thickness and Alfvénicity. However, the correlation between Alfvénicity and temporal duration may be partially influenced by instrumental limitations, as longer-duration events are more reliably resolved in plasma velocity measurements. This effect is evident in the spacecraft dependence: PSP, with its higher cadence, shows a much weaker correlation, whereas ARTEMIS and WIND, which operate at lower cadence, display a stronger apparent correlation. Other plasma parameters, such as plasma beta and alpha-particle abundance, show no significant correlation with $Q^\pm$, implying that the Alfvénic nature of current sheets is primarily governed by the local turbulent environment rather than by large-scale plasma conditions.

Since the normal component of the magnetic field plays a key role in determining both the spatial scale and the associated current density, we next examine the rotational characteristics of the current sheets and their relationship with the normalized normal magnetic field component, B_N/B . Figure 3.7 shows the distributions of the in-plane rotation angle (also referred to as the shear angle) and the normalized normal component B_N/B , along with their joint distributions for different missions. Panel (a) reveals that PSP observes a distinctly different distribution of rotation angles compared to the WIND and ARTEMIS missions, while the distributions of B_N/B are largely similar, as shown in Panel (b). This discrepancy suggests that the rotational structure of current sheets evolves significantly as the solar wind propagates from the near-Sun environment to 1 AU. The multiple peaks observed in the PSP shear-angle distribution likely reflect the coexistence of several current sheet populations. As the solar wind expands and mixes, this structured distribution becomes smoother, as observed by WIND and ARTEMIS near Earth. We note that the identification criteria and additional constraints imposed to ensure the reliability of the minimum variance analysis exclude some current sheets with small shear angles, which may contribute to the apparent single peak in the PDFs (Liu et al., 2023). However, current sheets with shear angles exceeding $\approx 30^\circ$ necessarily satisfy the selection criteria and are therefore unaffected. Consequently, the PDFs are considered reliable for $\omega_{\text{in}} > 30^\circ$.

The distribution of B_N/B is clearly bimodal, with one population corresponding to nearly field-aligned normals and another to nearly perpendicular normals. Only a small fraction

of events fall in the intermediate range. Such bimodal behavior is consistent with the coexistence of different types of discontinuities—most notably rotational and tangential discontinuities (Madar et al., 2024). We note, however, that our selection criteria may have different passing rates for different values of B_N/B , which could affect the relative amplitudes of the PDFs, though unlikely the presence of the bimodal structure itself (Liu et al., 2023).

Panel (c) shows the joint distribution of the in-plane rotation angle and B_N/B , where each column has been normalized to highlight how the rotation angle varies with B_N/B . The distinct distribution observed by PSP again indicates an evolutionary trend: current sheets closer to the Sun exhibit a more structured and varied rotational behavior, and they are smoother and more uniform at 1AU.

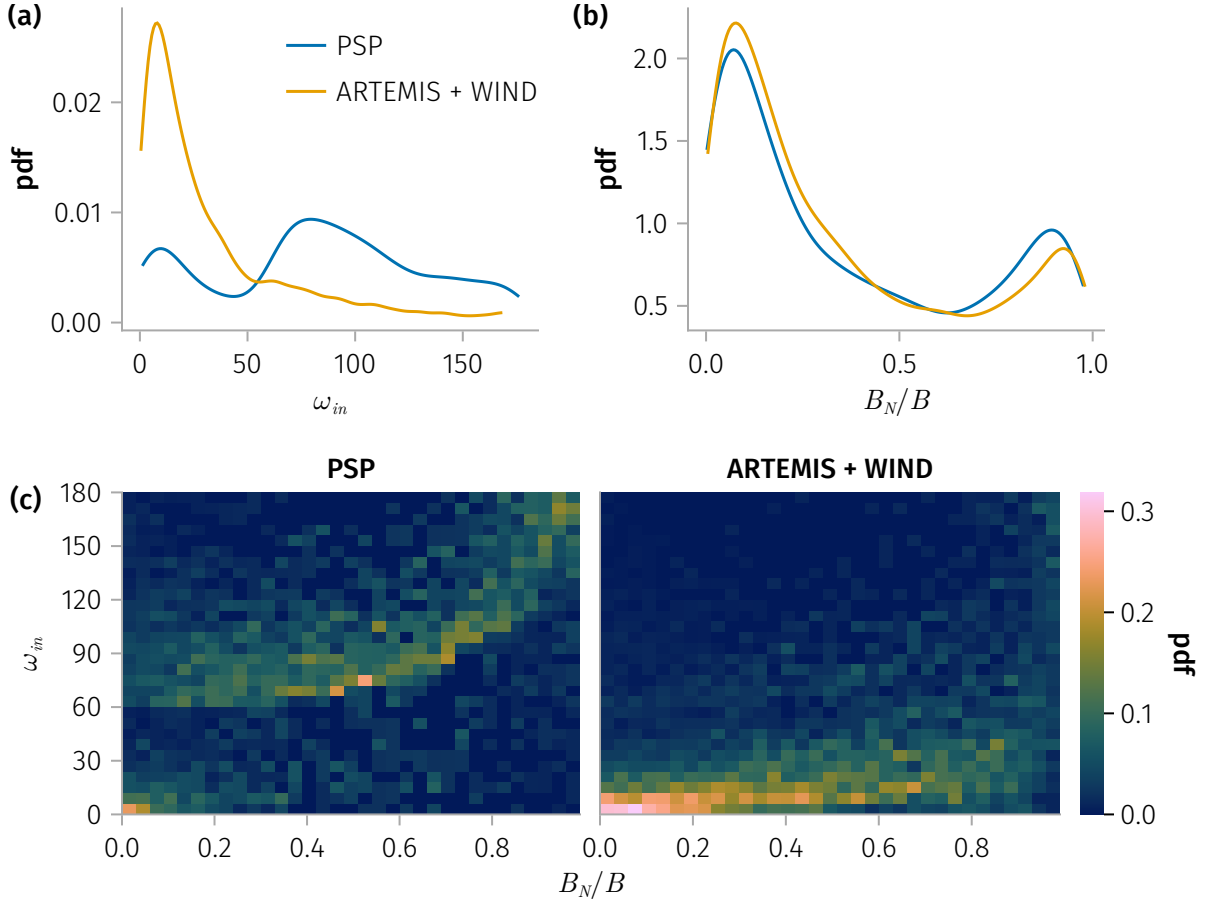


Figure 3.7: (a) Probability density functions of the in-plane rotation angle (ω_{in}) for PSP and ARTEMIS + WIND. (b) Probability density functions of the normalized normal magnetic field component (B_N/B). (c) Joint distributions of ω_{in} and B_N/B for PSP (left) and ARTEMIS + WIND (right).

Finally, Figure 3.8 presents the PDFs of current sheet temporal durations, Δt , observed by different missions. Under the assumption that current sheets propagate without significant relaxation, the temporal separation between different parts of a structure should remain unchanged between inner and outer spacecraft, independent of solar-wind acceleration (Berriot et al., 2024). As such, temporal duration provides additional diagnostic information on the nature and evolution of current sheets. The resulting distributions differ noticeably in shape, reflecting variations in the relative occurrence of short- and long-duration events across the datasets. In particular, changes in slope with increasing duration suggest the presence of at least two, and possibly three, distinct regimes contributing to the observed range of current sheet durations. The shortest-duration events are likely associated with kinetic-scale current sheets, while the longer-duration events may correspond to flux-tube boundaries, large-scale magnetic structures, or even heliospheric current sheet crossings (Borovsky, 2008; Liou & Wu, 2021). The similar slopes observed at longer durations across missions indicate that large-scale structures are relatively stable with heliocentric distance. In contrast, the short-duration population evolves more rapidly as the solar wind expands, either because such structures are generated locally by turbulence or because they are advected with the flow after being generated by turbulence much closer to the Sun.

Assuming that current sheets propagate radially without significant distortion or dissipation, the measured temporal duration can be interpreted as a proxy for the spatial thickness of the structure. This interpretation is modulated by the local magnetic field orientation but is not affected by solar wind acceleration. To account for geometric effects, we apply a correction based on the Parker spiral model by multiplying the PSP durations by a factor $\sin(\Theta_{\text{Earth}})/\sin(\Theta_{\text{PSP}})$. Here, $\Theta \approx \arctan(B_T/B_R)$ denotes the angle between the magnetic field and the radial direction, where B_R and B_T are the radial and transverse components of the magnetic field, respectively. Although this correction is a simplified approximation, it provides a useful scaling comparison: after adjustment, the PSP duration distribution aligns closely with those of WIND and ARTEMIS near 1 AU for short-duration current sheets. This agreement suggests that the shortest-duration (kinetic-scale) current sheets are predominantly oriented perpendicular to the mean magnetic field and evolve substantially with distance from the Sun.

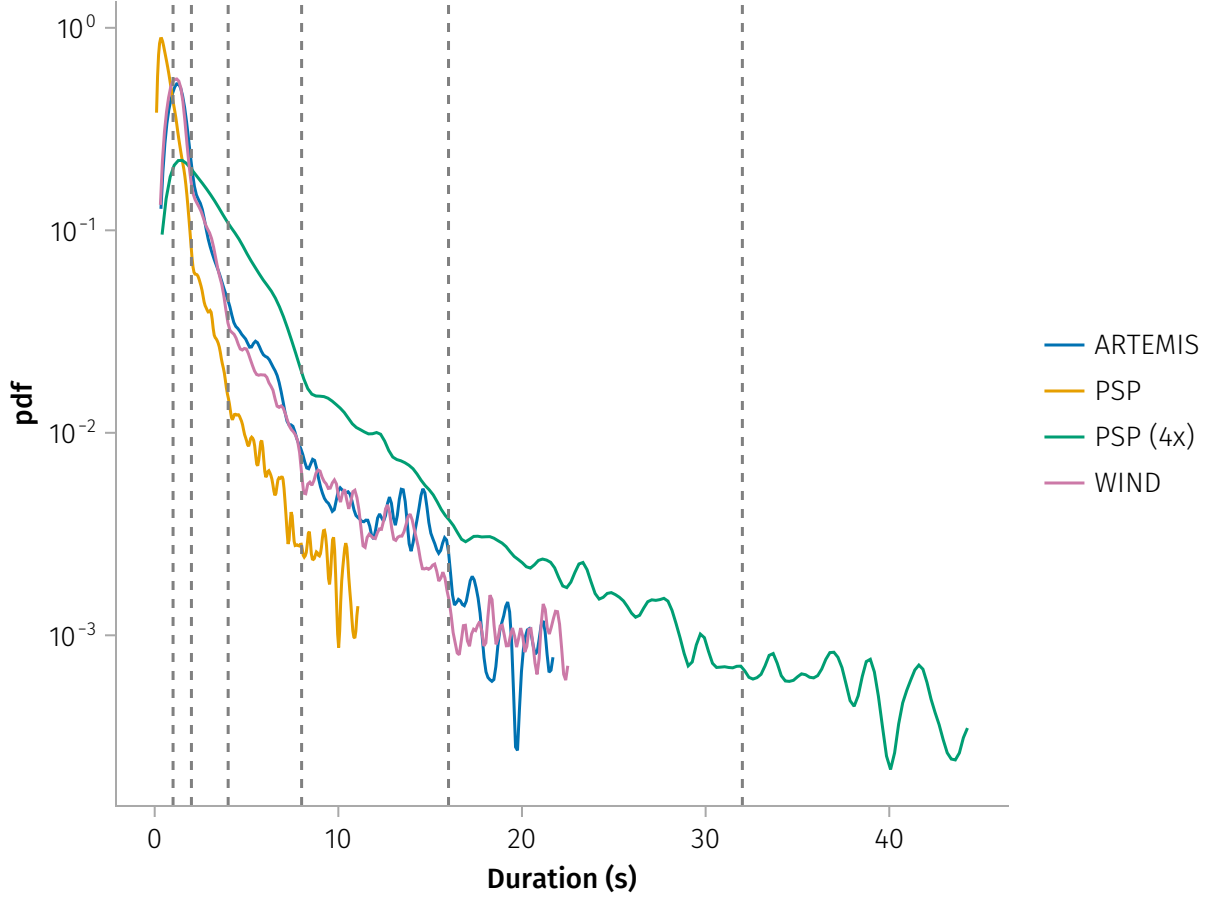


Figure 3.8: Probability density functions of current sheet durations (in seconds) observed by different missions. Grey vertical dashed lines indicate durations of 1, 2, 4, 8, 16, and 32 s (from left to right).

3.3 Conclusion

1. We investigated three Parker Solar Probe (PSP) encounters, complemented by ARTEMIS and WIND measurements, to identify and characterize current sheets across different heliocentric distances. The results indicate that variations in the selected time intervals exert only a minor influence on key current sheet properties such as thickness, current density, and Alfvénicity. This suggests that the observed evolution of current sheet characteristics primarily reflects spatial effects associated with radial expansion rather than temporal variability.
2. Our analysis confirms that current sheet properties are closely linked to local plasma conditions. In particular, the results extend previously reported scale-dependent rela-

tionships between current-sheet thickness and current density by more than two orders of magnitude, encompassing structures ranging from kinetic to large magnetohydrodynamic (MHD) scales. Despite substantial differences in absolute scales, the normalized current density remains nearly constant across radial distances, while the normalized current-sheet thickness exhibits only a modest increase with heliocentric distance. Variations in the median values are minor compared to the widths of the corresponding probability density functions, indicating that the intrinsic spread of current sheet properties dominates over systematic radial trends. The pronounced anti-correlation between current density and spatial scale—stronger current densities corresponding to thinner sheets—and the similarity of normalized current densities across radial distances indicate a close connection between current sheets and MHD turbulence, since localized, non-Gaussian current density enhancements are a hallmark of intermittency in turbulent plasmas.

3. The Alfvénicity of current sheets, quantified by the parameter Q , remains below unity for the majority of events. The magnitude ratios reported by PSP and WIND are broadly consistent, while PSP observations show smaller angular deviations than those from WIND and ARTEMIS. Pressure anisotropy alone does not account for the observed velocity and magnetic field jumps. Instead, the degree of Alfvénicity appears to be primarily controlled by the surrounding turbulent plasma state—specifically, by cross helicity and residual energy. Most current sheets exhibit low compressibility (typically $\beta < 0.1$). These findings support a picture in which current sheets are embedded within, and shaped by, the local turbulent cascade. In other words, the local macroscopic turbulence environment determines whether a boundary appears Alfvénic or non-Alfvénic when sampled in situ.
4. A comparison between PSP and near-Earth missions reveals that the statistical properties of solar wind current sheets undergo systematic evolution with heliocentric distance. Apparent differences are observed in the distributions of unnormalized current density, thickness, magnetic field jump, rotation angle, and temporal duration. Processes that may drive this evolution include global solar wind expansion (Matteini et al., 2012), nonlinear dynamics of Alfvén waves and Alfvénic turbulence (Medvedev et al., 1997), and interactions with other coherent structures. This evolution has important implica-

tions for the role of current sheets in plasma heating (Sioulas et al., 2022), particle energization and transport (Zhang et al., 2025b), which are expected to depend strongly on radial distance.

Taken together, our results support a picture where current sheets are predominantly turbulence-generated, dynamically evolving structures whose Alfvénic character is governed by the ambient solar wind turbulence properties—through cross helicity and residual energy. The sub-unity Alfvénicity and its dependence on ambient turbulence are further interpreted through the multifluid equilibrium model of Appendix A, which shows how interpenetrating ion populations can produce the observed velocity–Alfvén speed discrepancy. The tight coupling between current sheet intensity and spatial scale, the coexistence of at least two structural regimes, and the systematic radial evolution of their properties collectively point to a complex interplay between intermittent turbulence, solar wind expansion, and kinetic processes. Resolving these features will require higher-resolution particle measurements, multi-spacecraft observations, and dedicated kinetic modeling.

3.4 Supplementary Material

To assess the robustness of our results to the choice of coordinate system, we repeated our analysis using current sheet normals determined by the magnetic field cross-product method, rather than minimum variance analysis (MVA) as shown in Figure 3.9 and Figure 3.10. Comparison of Figure 3.9, Figure 3.10 and Figure 3.4, Figure 3.3 demonstrates that main results obtained via the two methods are very similar.

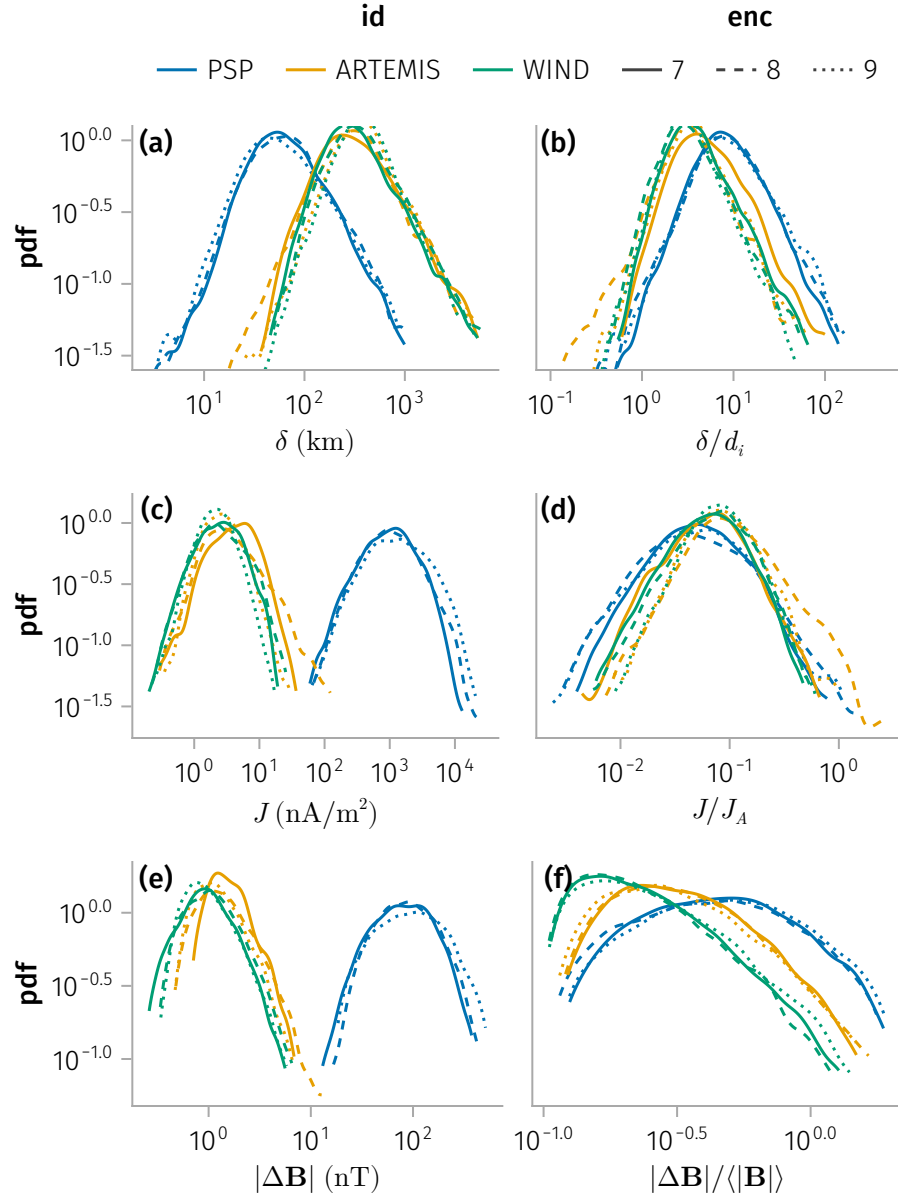


Figure 3.9: Same as Figure 3.3 but using cross product to determine the normal direction to the current sheet.

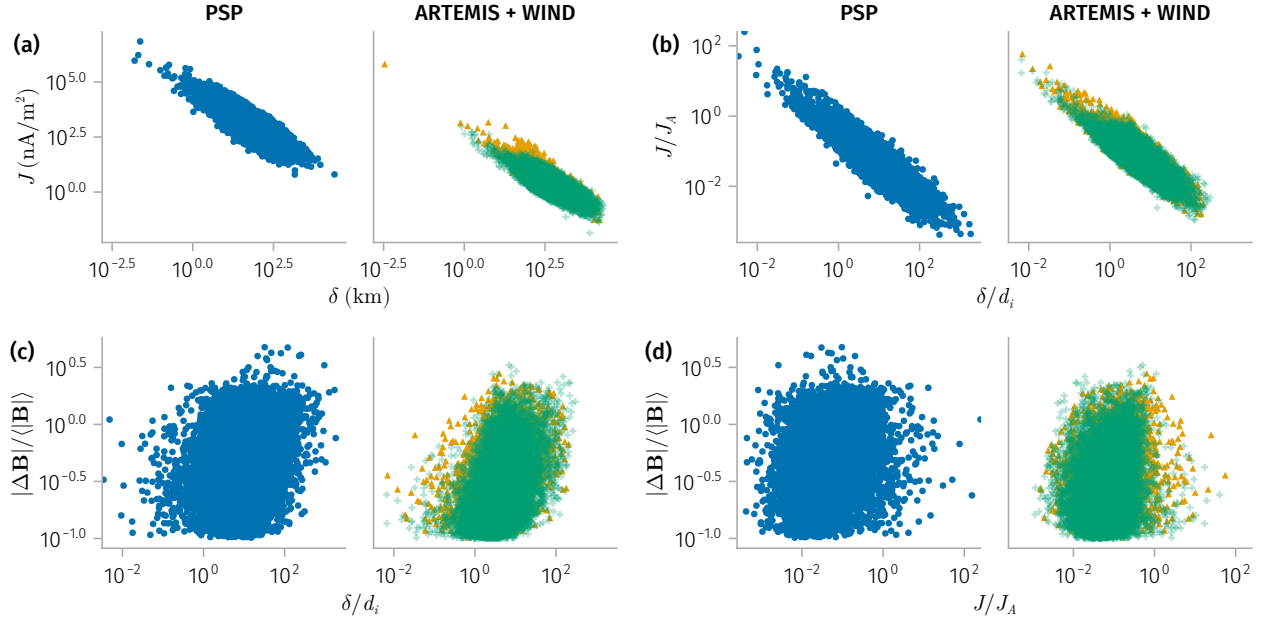


Figure 3.10: Same as Figure 3.4 but with current sheet normals determined using the magnetic field cross-product method instead of minimum variance analysis (MVA).

Chapter 4

Quantification of Particle Scattering by Solar Wind Current Sheets: Pitch-Angle Diffusion Rates

Current sheets—coherent structures arising from the turbulent energy cascade—act as efficient scatterers of energetic particles in collisionless plasmas (Artemyev et al., 2020a; De Giorgio et al., 2017; Malara et al., 2021; Perrone et al., 2020). Because they are ubiquitous throughout the heliosphere, their interaction with energetic particles is a systematic rather than incidental feature of particle transport, with implications for SEP modeling (Desai & Giacalone, 2016; Giacalone, 2013).

Despite extensive research on magnetic turbulence (Oughton & Engelbrecht, 2021; Pucci et al., 2016), the quantitative impact of coherent structures on particle transport remains insufficiently explored. Previous studies have primarily focused on idealized turbulence models (Giacalone & Jokipii, 1999; Matthaeus et al., 2003), often neglecting the specific role of coherent structures, such as current sheets, in the scattering of energetic particles. Investigations of interactions between rotational discontinuities (or groups of such discontinuities forming so-called switchbacks; see (Bale et al., 2019; Wit et al., 2020)) and energetic particles have demonstrated highly chaotic particle dynamics (Malara et al., 2021; 2023). However, previous studies focused on elucidating the basic mechanisms rather than quantifying scattering using realistic distributions in accordance with observations. This study aims to bridge that gap by providing a detailed analysis and quantification of particle interactions with current sheets, building on the observational characterization of current sheet properties across the inner heliosphere developed in Chapter 2 and Chapter 3. We adopt an analytical model of the magnetic field configuration that incorporates realistic statistical parameters derived from solar wind observations at 1 AU. By leveraging an exact Hamiltonian formulation that accounts for the rotational effects of the magnetic field, alongside test particle simulations, we investigate the evolution of particle pitch angles and the statistical long-term behavior of pitch-angle scattering across different particle energies.

This approach allows us to extend prior works (Whitman et al., 2023) about energetic particle modeling and references therein by incorporating realistic coherent structures.

The structure of this paper is as follows. In Section 4.1 we present a detailed description of the magnetic field model and the fundamental equations governing particle motion. In Section 4.2 we introduce the concept of adiabatic invariance and discuss its violations due to separatrix crossings in phase space. Section 4.3 presents numerical simulation results and statistical observations of current sheets in the solar wind. In Section 4.4 we analyze the long-term evolution of particle pitch angles due to multiple scatterings by current sheets. Finally, a discussion and conclusions are provided in Section 4.5.

4.1 Basic Equations

We assume the following 1-D force-free ($B = \text{const}$) magnetic field configuration where $\mathbf{B}$ depends only on the z coordinate across the current sheet surface:

$$\mathbf{B} = B(\cos \theta \mathbf{e}_z + \sin \theta(\sin \varphi(z) \mathbf{e}_x + \cos \varphi(z) \mathbf{e}_y)),$$

where B is the magnitude of the magnetic field, and θ is the azimuthal angle between the normal $\mathbf{B}_z = B \cos \theta \mathbf{e}_z \equiv B_n \mathbf{e}_z$ and the magnetic field. More specifically, we assume the following form: $\varphi(z) = \beta \tanh(z/L)$, where L is the thickness of the current sheet and the shear half-angle β is one half of the in-plane rotation angle ω_{in} . The transverse magnetic field $\mathbf{B}_t = B_t \sin \varphi(z) \mathbf{e}_x + B_t \cos \varphi(z) \mathbf{e}_y$ rotates by an angle ω_{in} from $-\infty$ to $+\infty$ where $B_t = B \sin \theta$. As an example, we present an observation from the ARTEMIS mission (Angelopoulos, 2011), which captures a magnetic field transition consistent with our model. Figure 4.1 shows the variations in $\mathbf{B}$, θ , and φ across the current sheet. The transverse field rotates smoothly, with φ following a hyperbolic tangent profile (note that time is linearly proportional to the spatial coordinate $z \approx v_n t$ where v_n is the solar wind velocity along the normal to the current sheet surface), while θ remains nearly constant near $\pi/2$, indicating a small normal component B_n . (A three-dimensional visualization of a typical current sheet magnetic field structure, represented by the magnetic field line, together with three representative particle trajectories is provided in Figure 4.5.)

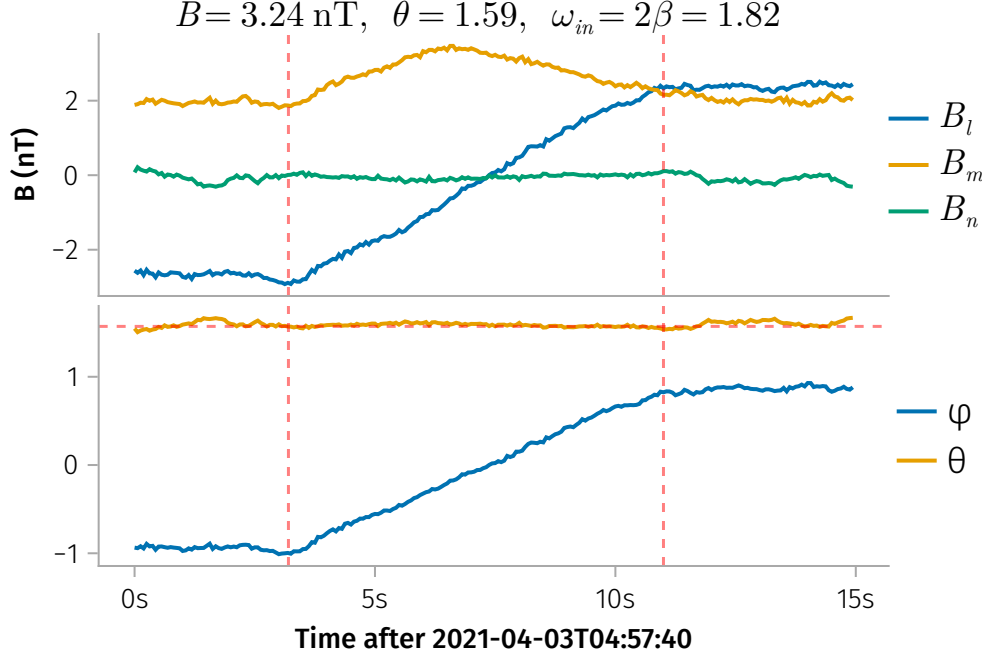


Figure 4.1: Example of a current sheet observed by ARTEMIS (Angelopoulos, 2011). Top: magnetic field in the current sheet **lmn** coordinate system (Sonnerup & Scheible, 1998) where l represents the maximum variance direction ($B_x = B_t \sin \varphi$ in our model), m the intermediate variance direction ($B_y = B_t \cos \varphi$), and n the minimum variance direction ($B_z = B \cos \theta$). Here, B_t and B represent the tangential and total magnetic fields, respectively (see text for detailed definitions). Bottom: variations of the azimuthal angle φ and the azimuthal angle θ across the current sheet. Vertical lines indicate the current sheet boundaries, and the horizontal line represents $\pi/2$. The analysis is based on magnetic field data with a 0.25-second resolution from the Fluxgate Magnetometer (Auster et al., 2008).

The motion of a charged particle in a pure magnetic field is governed by the Hamiltonian:

$$H = \frac{1}{2m}(\mathbf{p} - q\mathbf{A})^2$$

where $\mathbf{A}$ represents the magnetic vector potential and $\mathbf{p}$ the canonical momentum. In the context of our model, the magnetic vector potential $\mathbf{A}$ admits the following integrable form:

$$\begin{aligned} A_x &= LB_t f_1(z) \\ A_y &= LB_t f_2(z) + xB_n \\ A_z &= 0 \end{aligned}$$

$$\begin{aligned}
f_1(z) &= \frac{1}{2} \cos \beta [\text{Ci}(\beta s_+(z)) - \text{Ci}(\beta s_-(z))] \\
&\quad + \frac{1}{2} \sin \beta [\text{Si}(\beta s_+(z)) - \text{Si}(\beta s_-(z))], \\
f_2(z) &= \frac{1}{2} \sin \beta [\text{Ci}(\beta s_+(z)) + \text{Ci}(\beta s_-(z))] \\
&\quad - \frac{1}{2} \cos \beta [\text{Si}(\beta s_+(z)) + \text{Si}(\beta s_-(z))]
\end{aligned} \tag{6}$$

and $s_{\pm}(z) = 1 \pm \tanh(z/L)$, Ci and Si are the cosine and sine integral functions (Abramowitz & Stegun, 1972).

We introduce a dimensionless Hamiltonian $\tilde{H} = H/h$ by normalizing $(x, z) = (\tilde{x}L + C_x, \tilde{z}L)$ and $(p_x, p_z) = p(\tilde{p}_x, \tilde{p}_z)$ where $p = qLB_t/c$ and $h = q^2L^2B_t^2/mc^2$. Note that because $\partial H/\partial y = 0$, $p_y = \text{const}$ and we could let $C_x = cp_y/qB_n$ to eliminate p_y :

$$\tilde{H} = \frac{1}{2} \left((\tilde{p}_x - f_1(z))^2 + (\tilde{x} \cot \theta + f_2(z))^2 + \tilde{p}_z^2 \right)$$

This is an exact Hamiltonian of a charged particle, incorporating the effect of magnetic field rotation characterized by the shear angle β . Unlike previous studies that rely on Taylor expansions near the current sheet center $z = 0$ (Artemyev et al., 2013a; Vainchtein et al., 2005; Zelenyi et al., 2013), we retain the full, unexpanded form. However, for comparison, we note that expanding the Hamiltonian to third order around the current sheet center and assuming $\beta = 1$ yields a reduced form structurally similar to that used in Artemyev et al. (2020a), albeit with a different normalization scheme. In this study, we quantitatively investigate the influence of shear half-angle (β) and particle energy ($E = H/h$) on the efficiency of pitch-angle scattering. For simplicity, the tilde notation over dimensionless variables is omitted in the following discussion.

4.2 Adiabatic Invariance and Its Violations at Separatrix Crossings

For current sheets where $B_n/B_t \ll 1$, the variables $(\kappa x, p_x)$ evolve significantly more slowly compared to (z, p_z) along particle trajectories (with $\dot{p}_x \propto \kappa$, where $\kappa = \cot \theta$). Assuming

that x and p_x are effectively frozen, the Hamiltonian describes periodic motion within the (z, p_z) plane, governed by the effective potential energy $U(z) = H - p_z^2/2$. When variations in $(\kappa x, p_x)$ occur on a timescale much longer than the fast oscillations in (z, p_z) , the generalized magnetic moment $I_z = (2\pi)^{-1} \oint p_z dz$ is approximately conserved as an adiabatic invariant with exponential accuracy (Neishtadt, 2000). Far from the current sheet, where the magnetic field is nearly uniform ($|z/L| \gg 1$), the pitch angle defined by $\alpha = \arccos \mathbf{B} \cdot \mathbf{v}/|\mathbf{B}||\mathbf{v}|$ remains constant (i.e., $\partial\alpha/\partial\mathbf{r} = 0$), where $\mathbf{v}$ is the velocity, $\mathbf{B}$ is the magnetic field, and $\mathbf{r}$ is the position. Since the simultaneous conservation of energy and I_z fully determines the motion of the particle, the velocity $\mathbf{v}$ can be expressed as a function of position $\mathbf{r}$, invariant I_z , and energy E : $\mathbf{v} = \mathbf{v}(\mathbf{r}, I_z, H)$. Given that energy is exactly conserved in a static magnetic field, the pitch angle α depends solely on I_z . Therefore, in the absence of I_z destruction, there is no pitch-angle scattering across the current sheet.

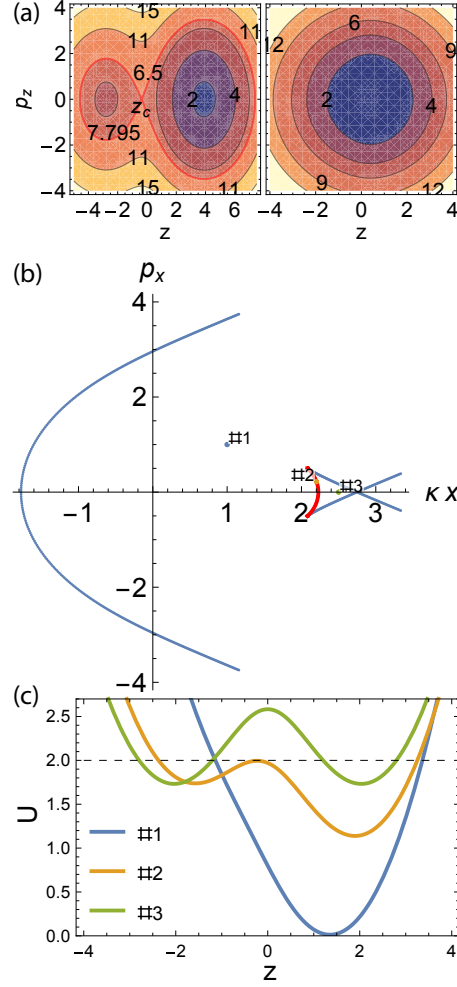


Figure 4.2: (a) Phase portraits of the Hamiltonian in the plane of (z, p_z) at fixed $(\kappa x, p_x)$ for $\beta = 1$. Each curve corresponds to a specific H , indicated on the plots. The left panel corresponds to $\kappa x = 4, p_x = 1$, while the right panel corresponds to $\kappa x = 0, p_x = 0.5$. (b) Phase plane of the Hamiltonian in the $(\kappa x, p_x)$ space. The red line represents the uncertainty curve and the blue line delineates the boundary encompassing all possible phase points. (c) Potential energy profiles defined by $U(z) = H - p_z^2/2$ at different locations in the $(\kappa x, p_x)$ place, corresponding to the labeled positions (#) in panel (b).

The Hamiltonian admits two distinct types of particle motion in the (z, p_z) plane, as illustrated in Figure 4.2(a). In the left panel, there are two potential wells in $U(z)$, resulting in three possible types of orbits in the (z, p_z) plane depending on the value of H : particles can move (oscillate) within one of local $U(z)$ minima, or can move outside these minima along *figure-eight* orbits. In contrast, the right panel represents a case with only one possible type of orbits in the (z, p_z) plane for a fixed H . As $(\kappa x, p_x)$ evolve slowly, the particle's trajectory in the (z, p_z) plane undergoes a gradual transformation. Transitions between motion types can occur, accompanied by significant trajectory reconfigurations when the particle crosses the separatrix, the curve separating motion within one of two local minima of $U(z)$ and motion along *eight-like* orbit (separatrix is shown by red bold line in Figure 4.2(a)). Near the separatrix, the instantaneous period of motion in the (z, p_z) plane increases logarithmically, diverging as the trajectory approaches it (Lichtenberg & Lieberman, 1983). When the timescale (period) of fast oscillations in the (z, p_z) plane and variations in the control parameter (κx) become comparable, the particle accumulates a nonvanishing change in the adiabatic invariant, resulting in a jump in I_z (Cary et al., 1986; Neishtadt & Vasiliev, 1999). Concurrently, the projection of the particle's phase point onto the $(\kappa x, p_x)$ plane lies along the so-called uncertainty curve shown by red bold line in 4.2, where each point on the curve corresponds to a particle trajectory in (z, p_z) coinciding with the separatrix.

The jump of I_z due to the separatrix crossing comprises two distinct components. The first component, termed the *dynamical jump*, arises from the singularity of the period of motion in the vicinity of the separatrix and, in our asymmetric case of the (z, p_z) plane about the z -axis (stemming from the term in f_1) is proportional to $\kappa \ln \kappa$ (Neishtadt, 2019, and references therein), resulting in slight changes to particle trajectories. The second component, referred to as the *geometric jump*, corresponds to the difference between the areas enclosed by the particle's trajectory within one of the separatrix wells and the area in the external region outside the separatrix. For instance, when a particle drifts from the boundary immediately before crossing, the total area enclosed by the separatrix increases to the value of the adiabatic invariant, $I_0 = (2\pi)^{-1} S(\kappa x, p_x)$. Upon crossing, the adiabatic invariant I_z undergoes a jump to approximately the area of the left well $S_l(\kappa x, p_x)$ or the right well $S_r(\kappa x, p_x) = S(\kappa x, p_x) - S_l(\kappa x, p_x)$, reflecting the reduction in the accessible phase space area for the particles. This geometric jump is independent of κ and of order

unity (Neishtadt, 2019, and references therein). For a single separatrix crossing and small values of κ , this jump of adiabatic invariance arises primarily from geometric destruction (Artemyev et al., 2020a). In symmetric Hamiltonians – where $U(-z) = U(z)$ – the differences in the enclosed areas during two successive crossings effectively cancel: the area deficit incurred when entering one of two wells is offset by the excess upon exiting, so that the net geometric jump over two crossings is zero (Büchner & Zelenyi, 1989; Neishtadt & Vasiliev, 1999). However, in our case, the term $f_1(z)$ introduces an asymmetry in the (z, p_z) plane see 4.2, leading to an asynchronous evolution of the two areas. As a result, the difference in areas at each crossing does not cancel between successive crossings. This produces a nonzero change in I_z that enhances pitch-angle scattering and drives rapid chaotization of the particle dynamics (Artemyev et al., 2013a; 2020a).

Due to the symmetry of particle motion about the $p_z = 0$ line, the potential energy $U(z)$ reaches a local maximum along the z -direction at the saddle point $z = z_c, p_z = 0$ of the separatrix (shown as z_c in Fig. (left panel)). At this point, conditions $\partial U / \partial z = 0$ and $\partial^2 U / \partial z^2 < 0$ are satisfied. These conditions allow us to express the slow variables along the uncertainty curve in the $(\kappa x, p_x)$ plane as functions of z_c . When a particle trajectory crosses the $z = 0$ plane, the crossing point is confined within a circular region defined by $(p_x - f_1(0))^2 + (\kappa x + f_2(0))^2 = 2H$. The likelihood of the trajectory intersecting the uncertainty curve is therefore approximately proportional to the uncertainty curve length L_{uc} , normalized by the square root of the particle energy, $\sqrt{H}$, as illustrated in Figure 4.3. For fixed H , $L_{uc} / \sqrt{H}$ increases with β , indicating higher scattering probabilities at larger magnetic field rotation angles. Similarly, at a fixed β , $L_{uc} / \sqrt{H}$ increases with H , suggesting that high-energy particles are more susceptible to pitch-angle scattering. Next, we will demonstrate these changes using test particles in realistic fields, to characterize their properties as functions of system parameters.

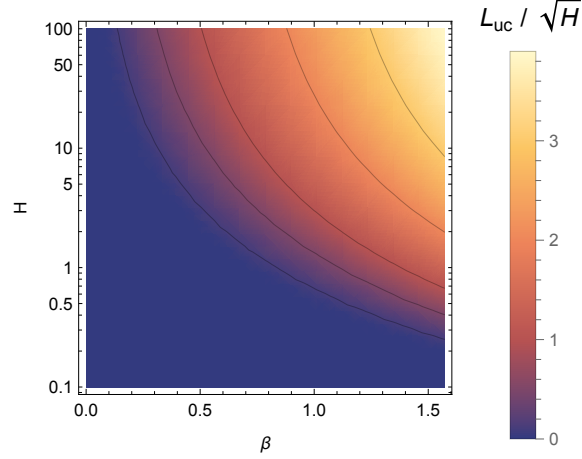


Figure 4.3: The uncertainty curve length $L_{\text{uc}}/\sqrt{H}$ as a function of β and normalized particle energy H .

4.3 Test Particle Simulations

To quantitatively analyze how particles are scattered by solar wind current sheets, we conducted extensive test particle simulations using a dataset of solar wind current sheets at 1 AU. Since the primary focus is on protons, the particle mass was set to m_p (proton mass) and the charge to the elementary charge $q = e$. According to the dimensionless Hamiltonian, the critical current sheet parameters that influence particle dynamics are angles θ and $\beta = \omega_{in}/2$, along with the parameter $B_t L$, which appears in the normalization factors p and $h = \frac{q^2 L^2 B_t^2}{mc^2}$. By a simple transformation, $B_t = B \sin \theta$, the key current sheet parameters become θ , ω_{in} , and $\tilde{v}_B \equiv v_B/c$, where $v_B \equiv qBL/(m_p c) = \Omega L$ and Ω is the proton gyrofrequency associated with the magnetic field B .

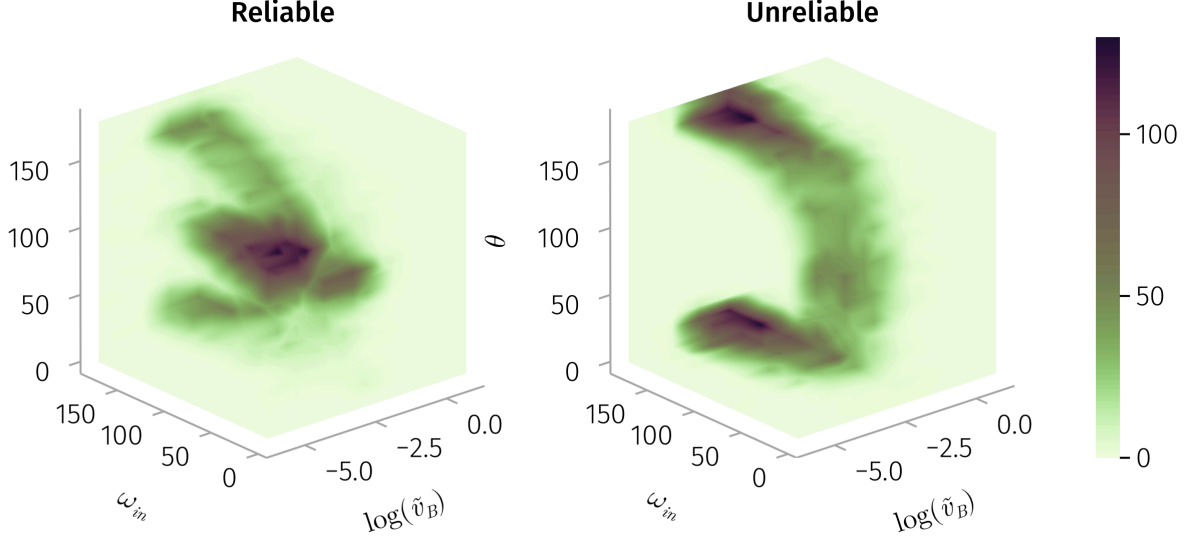


Figure 4.4: 3D density plots of the azimuthal angle θ , in-plane rotation angle ω_{in} , and logarithm of the characteristic velocity $\log \tilde{v}_B$. The left panel corresponds to cases where the MVAB accuracy conditions are satisfied, while the right panel represents cases where they are not satisfied.

Using data from the ARTEMIS (Angelopoulos, 2011) and the Wind mission (Acuña et al., 1995), we compiled a dataset of 100000 current sheets (Liu et al., 2022b; Zhang et al., 2025a). The orientations of these current sheets were determined using the minimum variance analysis of the magnetic field (MVAB) method (Sonnerup & Scheible, 1998). Accurate orientation determination was crucial for estimating the thickness of the current sheets (L) and the in-plane magnetic field rotation angle (ω_{in}), both of which significantly influence particle scattering. To ensure reliability, only current sheets with $\Delta|B|/|B| > 0.05$ or $\omega > 60^\circ$ were used in the following analysis, as these conditions improve the accuracy of the MVAB method, as noted by . Note, these conditions do not constrain the discontinuity normal. An alternative approach to orientation determination (Knetter et al., 2004; Wang et al., 2024) involves using the cross-product method to estimate the normal orientation and is largely based on the assumption that B_n is effectively zero. Figure 4.4 shows 3D density plots of the azimuthal angle θ , the in-plane rotation angle ω_{in} , and logarithm of the characteristic velocity $\log \tilde{v}_B$, categorized by whether the MVAB accuracy conditions are satisfied (left for accurate, right for not accurate). Current sheets with accurately determined orientations typically have smaller azimuthal angles θ , indicating a smaller B_n , and moderate in-plane rotation angles ω_{in} . In contrast, current sheets with

potentially inaccurate normal orientations display larger θ (larger B_n) and larger ω_{in} . The most probable values observed in the distribution are a characteristic velocity (v_B) of approximately 500 km/s (which corresponds to a typical energy ~ 1 keV), an in-plane rotation angle (ω_{in}) near 100 degrees, and an azimuthal angle (θ) around 85-95 degrees.

For each magnetic field configuration, we initialize an ensemble of particles far away from the current sheet center (i.e., with an initial z position satisfying $|z_0| > 6L + 2r_g$, where r_g is the gyro radius). The particles are uniformly binned in pitch angle (α_0) from 0° to 180° in 180 bins of size $\Delta\alpha = 1^\circ$, with gyro phase (ψ_0) uniformly sampled from 0° to 360° in 120 bins of size $\Delta\psi = 3^\circ$. In this simulation, the current sheet is consistently configured with a positive B_z component. Consequently, particles with an initial positive pitch-angle cosine $\mu \equiv \cos \alpha$ ($\alpha_0 < 90^\circ$; $\mu_0 > 0$) are interpreted to originate below the current sheet (and move toward the current sheet), while those with a negative cosine ($\alpha_0 > 90^\circ$; $\mu_0 < 0$) are considered to come from above it (and move toward the current sheet). The particle trajectories are then numerically integrated until each particle fully exits the current sheet ($|z(t)| > |z_0| + 2r_g$). Figure 4.5 shows three representative particle trajectories in a typical magnetic field configuration characterized by $\beta = 75^\circ$ and $\theta = 85^\circ$. All particles have the same initial pitch angle $\alpha_0 = 90^\circ$ and velocity $v_p = 8v_B$, but differ slightly in their initial gyrophases: $\phi_0 = 163.3^\circ, 164.4^\circ$, and 165.6° . These cases illustrate distinct scattering behaviors: one particle exhibits a negligible change in pitch angle, another undergoes a finite pitch-angle deflection, and the third is reflected by the current sheet. For each trajectory, the final pitch angle α_1 is recorded. These pitch angles are then organized into bins to construct a transition matrix (TM), also known as a stochastic matrix (Durrett, 2016), which represents the probability distribution of pitch-angle changes resulting from a single particle interaction with the current sheet.

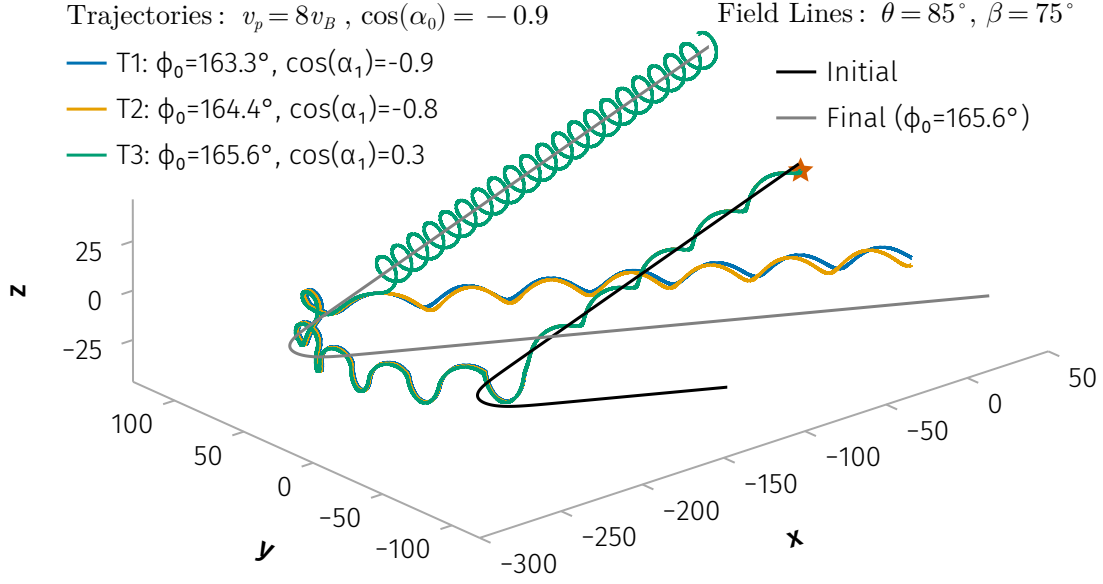


Figure 4.5: Three particle trajectories (T1, T2, T3) with identical initial pitch angles ($\alpha_0 = 90^\circ$) and velocity $v_p = 8v_B$, but slightly different initial gyrophases ($\phi_0 = 163.3^\circ, 164.4^\circ, 165.6^\circ$) in a representative magnetic field profile ($\beta = 75^\circ, \theta = 85^\circ$). The orange star marks the initial particle position. The black and gray lines represent the magnetic field lines to which the reflected particle (T3) is initially and finally attached, respectively, before and after interaction with the current sheet.

Figure 4.6 illustrates the transition matrix for 100 keV particles (velocity $v_p \approx 4000$ km/s) under four magnetic field configurations: (i) $v_B = 500$ km/s, $\theta = 85^\circ$, $\beta = 50^\circ$; (ii) $v_B = 500$ km/s, $\theta = 85^\circ$, $\beta = 75^\circ$; (iii) $v_B = 500$ km/s, $\theta = 60^\circ$, $\beta = 50^\circ$; and (iv) $v_B = 4000$ km/s, $\theta = 85^\circ$, $\beta = 50^\circ$. Enhanced probability along the diagonal corresponds to weakly scattered particles ($\Delta\alpha = \alpha_1 - \alpha_0 \approx 0$), while spreading around the diagonal reflects diffusive scattering. Large pitch-angle jumps are represented by non-diagonal elements.

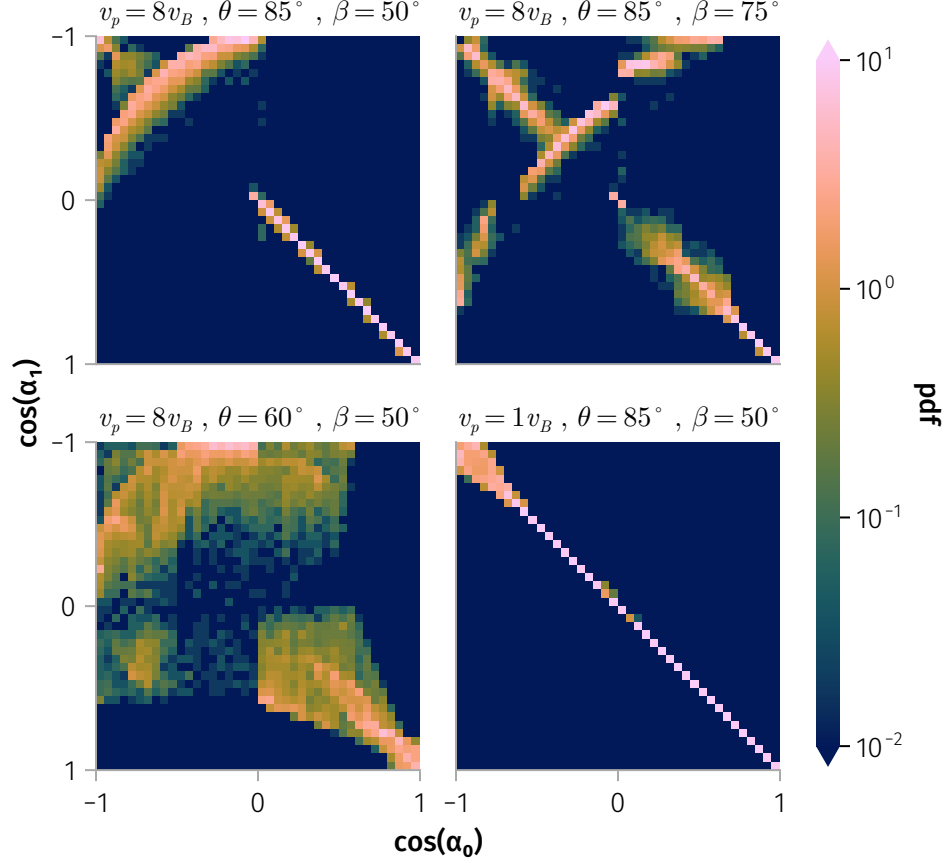


Figure 4.6: Transition matrix for 100 keV protons under four distinct magnetic field configurations: (i) $v_p = 8v_B$, $\theta = 85^\circ$, $\beta = 50^\circ$; (ii) $v_p = 8v_B$, $\theta = 85^\circ$, $\beta = 75^\circ$; (iii) $v_p = 8v_B$, $\theta = 60^\circ$, $\beta = 50^\circ$; and (iv) $v_p = v_B$, $\theta = 85^\circ$, $\beta = 50^\circ$.

The transition matrix color maps for various current sheet configurations reveal that particle pitch-angle evolution during multiple current sheet crossings is determined by a combination of weak/strong diffusion and large jumps. For example, in current sheets with a typical shear half-angle $\beta = 50^\circ$ and azimuthal angle $\theta = 85^\circ$ (configuration (i)), particles entering from above the sheet ($z > 0$; assuming positive B_n) often experience significant pitch-angle jumps or strong diffusion. In contrast, particles entering from below the sheet

($z < 0$) typically undergo minimal pitch-angle changes. Occasionally, interactions with current sheets having very large shear half-angles (β , e.g., configuration (ii)) or smaller azimuthal angles (θ , e.g., configuration (iii)) result in enhanced diffusion and the reflection of certain particles from the current sheet, indicated by a reversal in the sign of $\cos \alpha$. For high-energy particles, interactions with current sheets of comparable characteristic speed ($v_B \sim v_p$, configuration (iv)) are characterized by weak scattering occurring only over a narrow range of pitch angles. The interplay between non-diffusive jumps and continuous diffusive processes drives a dynamic evolution of the particle ensemble.

4.4 Long-Term Pitch Angle Evolution

Modeling the long-term effect of particle pitch-angle scattering by current sheets involves simulating the dynamics of a large number of particles through multiple current sheet interactions over extended periods. To reduce computational time and complexity of such simulations and introduce scattering effects into existing transport models, we derive a simplified probabilistic description of pitch-angle evolution. The scattering process depends on the particle's initial conditions, $(\mathbf{r}, \mathbf{v})$, as well as the configuration of the current sheet, $\mathbf{B}$. In the 1D model, these initial conditions can be expressed in terms of z, E_0, α_0 , and ψ_0 . Since our primary interest lies in the pitch angle after the particle exits the current sheet, and the energy E_0 remains constant in the absence of an electric field, the initial energy E_0 and position z (provided that the particle is sufficiently far from the center of the current sheet) can be omitted from further consideration.

The final pitch angle, however, is highly sensitive to initial conditions (α_0, ψ_0) , where small variations in the gyro phase can lead to significantly different final pitch angles (Malara et al., 2021). Therefore, the scattering process $\Pi : (\alpha_0, \psi_0) \rightarrow (\alpha_1, \psi_1)$ is better represented as a probabilistic transition $p(\alpha_1 | \alpha_0, \Pi)$, with the probability derived by numerical interpolation in the α_1 -space. Here, Π characterizes the current sheet configuration. This probabilistic representation is further motivated by the fact that the gyro phase depends on the particle's location and may undergo random shifts during the crossing of a current sheet. Additionally, numerical integration methods, such as the Boris method, introduce a phase error proportional to Δt , making the gyro phase less reliable. Thus,

it is more appropriate to model the gyro phase as a random variable. This probabilistic approach eliminates the dependence on the gyro phase, instead focusing on the statistical relationship between the initial pitch angle α_0 and the final pitch angle α_1 , as governed by the properties of the current sheets.

For particles with a specific energy, a (weighted-average) mixture distribution (Frühwirth-Schnatter, 2006) can be constructed based on the observed distribution of solar wind discontinuities (SWDs): $p(\alpha_1 | \alpha_0) = \sum_i p(\alpha_1 | \alpha_0, \Pi_i) w_i$, where the weight w_i corresponds to the empirical probabilities of specific SWD configurations. After binning, this yields a weighted transition matrix (WTM), which represents the varying likelihoods of particles encountering Sw Ds with different properties and encapsulates the overall probability of a particle undergoing a pitch-angle jump due to interactions with an ensemble of SWDs at 1 AU.

As illustrated in Figure 4.7, the WTM for 100 keV protons at 1 AU shows a strong likelihood of minimal changes in pitch angle, as evidenced by the bright diagonal. However, there exist significant probabilities associated with diffusive scattering and with large pitch-angle changes. The latter arise mainly from interactions with current sheets whose characteristic scales (L) are comparable to or smaller than the gyroradius of (in this case) 100 keV protons. Such strong scattering cannot be adequately described by diffusion alone. However, the mapping described in Equation~ enables the direct application of the mixture distribution for simulating the long-term evolution of particle pitch-angle distributions (such map is a discretized approximation of stochastic differential equations that describe particle dynamics with a given scattering probability; see (Artemyev et al., 2020c; Jacod & Protter, 2012; Tonoian et al., 2023; Ukhorskiy et al., 2011)):

$$\alpha_{n+1,i} = W_{\Pi}(\alpha_{n,i}, \xi_{n,i}) \quad (7)$$

where n is the number of interactions (with SWDs), i is the particle index within the ensemble, and W_{Π} determines the subsequent pitch angle from the mixture distribution, using the previous pitch angle and a uniformly sampled random variable $\xi_{n,i}$.

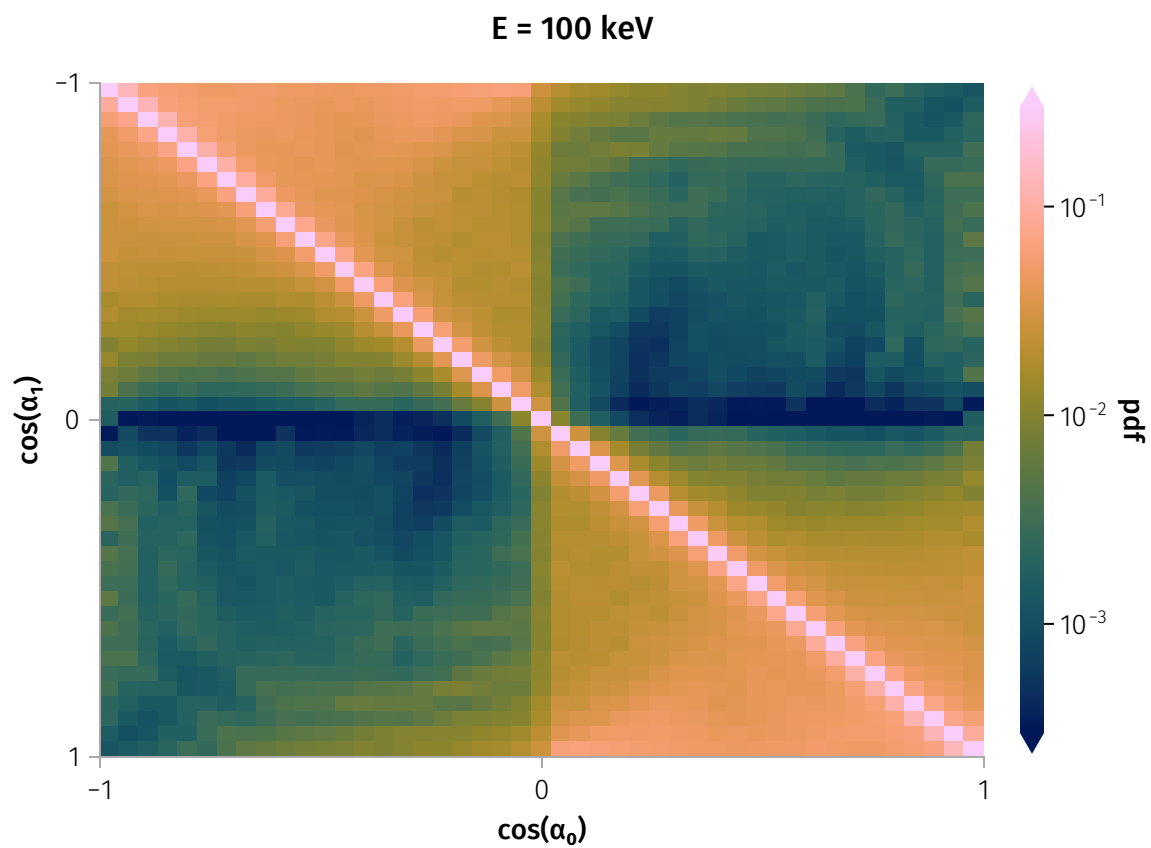


Figure 4.7: Weighed transition matrix for 100 keV particles constructed from the observed distribution of current sheet at 1 AU.

Figure 4.8 illustrates two representative solutions of the dynamical pitch-angle mapping equation derived from the mixture distribution at 1 AU for 100 keV and 1 MeV protons. A key feature of the pitch-angle dynamics is the occurrence of infrequent but substantial jumps, including rare, large-angle changes that can lead to particle reflection from the current sheet.

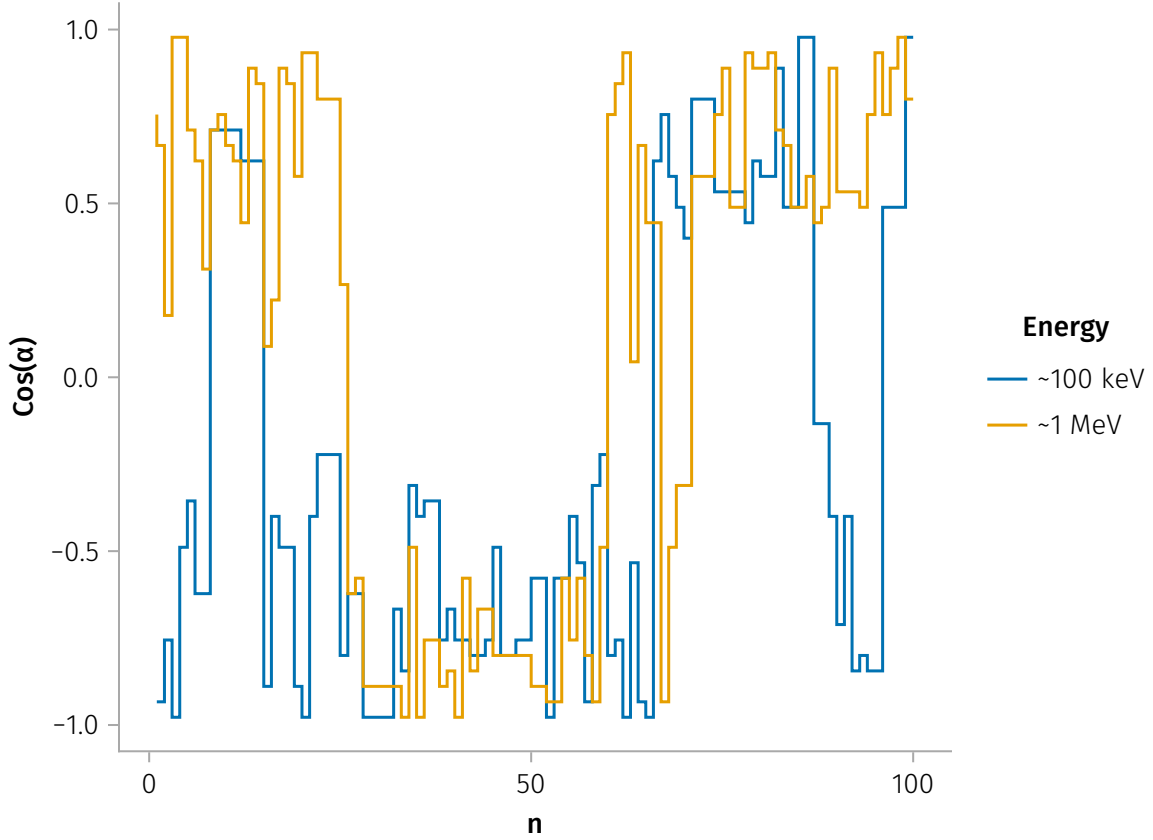


Figure 4.8: Examples of particle pitch-angle scattering by solar wind current sheets for 100 keV and 1 MeV protons.

However, directly incorporating the mapping (or stochastic difference equations) derived from the mixture distribution into classical numerical schemes for transport-diffusion equations is a complex task (see discussion in (Litvinenko & Noble, 2013; Mykhailenko et al., 2024; Strauss & Effenberger, 2017)). To facilitate comparison with other scattering processes and allow inclusion of SWD-induced scattering effects in such models, we evaluate the effective scattering rate, $D_{\mu\mu}$. This rate acts as a global diffusion coefficient, independent of the local pitch angle, since high-energy particles frequently experience large

pitch-angle jumps, leading to strong mixing. The scattering rate depends on the particle energy and the mixture distribution (i.e., the distribution of current sheets). Using the mapping described in Equation~ for an ensemble of particles, we calculate the evolution of the second moment of the pitch-angle distribution for the particle energy range from 100 keV to 1 MeV for current sheets at 1 AU:

$$M_1(n) = N^{-1} \sum_{i=1}^N (\alpha_{n,i} - \alpha_{0,i})$$

$$M_2(n) = N^{-1} \sum_{i=1}^N (\alpha_{n,i} - \alpha_{0,i})^2 - M_1^2(n)$$

where $M_1(n)$ represents the mean drift in pitch-angle, and $M_2(n)$ quantifies the spreading in pitch-angle. The function $M_2(n)$ increases linearly with the number of interactions with current sheets before reaching saturation, where the pitch-angle distribution becomes totally mixed. This behavior is illustrated in Figure 4.9. The rate of such mixing is described by $D_{\mu\mu}$, which can be evaluated by fitting $M_2(n)$ to an exponential model, $M_2(n) = d - ae^{-D_{\mu\mu}n}$, where d is the saturated second moment and a is the slope of the exponential fit. This model assumes that at early stages (small n), particles undergo diffusive mixing, with $M_2(n) \propto D_{\mu\mu}n$. At later stages (large n), the distribution becomes fully mixed, and M_2 asymptotically approaches a constant value, $M_2 \approx M_2(\infty)$.

To translate the number of interactions n into a physical time, we consider the occurrence rate of SWD (Vasko et al., 2022; Zhang et al., 2025a) and the average solar wind speed. Using these parameters, we can estimate the average distance between SWDs. Assuming that protons travel freely between interactions at velocities $v_p \sim \sqrt{H}$, we can then derive the characteristic time interval between consecutive encounters with discontinuities. This enables the transition from a discrete interaction-based framework ($D_{\mu\mu}$) to a continuous temporal description ($\mathcal{D}_{\mu\mu}$), making it suitable for realistic modeling of particle dynamics and enabling direct incorporation of derived diffusion rates into transport-diffusion simulations. This approach provides a simplified yet effective means to account for current-sheet-induced scattering in broader models of energetic particle dynamics.

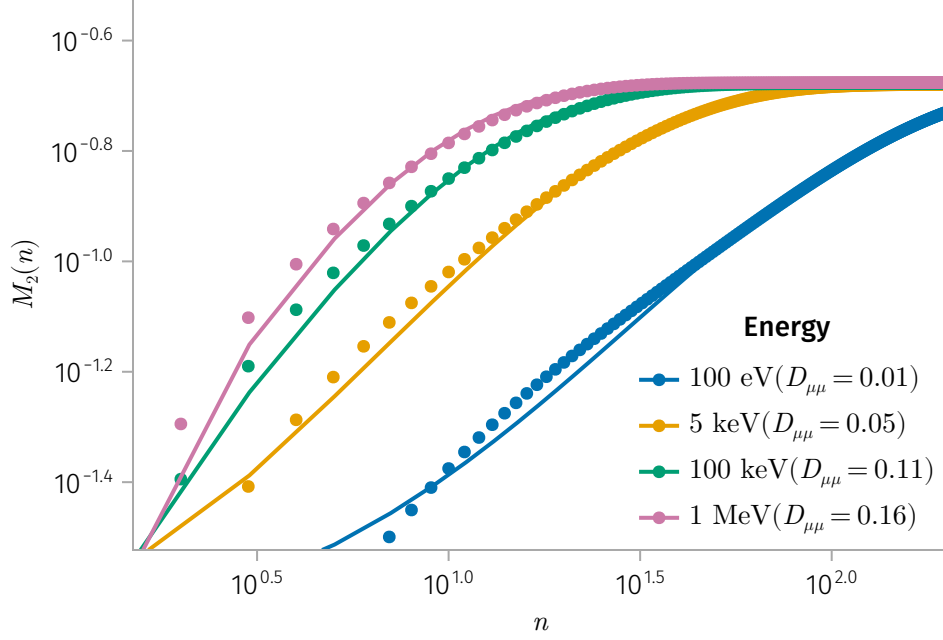


Figure 4.9: Top: Second moment of the pitch-angle distribution, $M_2(n)$, as a function of interaction number (n) for different particle energies (100 eV, 5 keV, 100 keV, 1 MeV), The estimated mixing rates, $D_{\mu\mu}$, are indicated in the legend. Bottom: Pitch-angle diffusion rates $\mathcal{D}_{\mu\mu}$ as a function of particle energy E .

4.5 Conclusion

In this study, we have investigated the scattering of energetic particles by current sheets in the solar wind and developed a model that incorporates the rotational effects β , the magnetic field magnitude B , and the current sheet thickness L . Our findings indicate that current sheets characterized by large rotation angles or relatively small characteristic velocities, defined as $\tilde{v}_B = \frac{qBL}{mc^2}$, can effectively scatter energetic particles. These scattering effects go beyond the conventional diffusion framework, as large pitch-angle jumps lead to rapid particle mixing in pitch-angles. Leveraging extensive observations of solar wind current sheets at 1 AU, we have provided a statistical estimate that quantifies the long-term scattering rate of energetic particles due to current sheets.

In the heliosphere, beyond 1AU, the background magnetic field strength decreases approximately as $\sim 1/r$ with increasing radial distance, where the azimuthal component B_ϕ dominates and $B \approx B_\phi \sim 1/r$. The magnitude of the current sheet magnetic field (B) scales accordingly with the background field (Zhang et al., 2025a). Based on recent observations,

the current sheet thickness, L , scales with the ion inertial length, $d_i \propto 1/\sqrt{N}$, which increases with radial distance due to the decline in plasma density, $N \propto 1/r^2$ (Maruca et al., 2023). Consequently, the characteristic velocity $\tilde{v}_B \propto BL$ remains nearly constant with the radial distance, implying that energetic particles consistently undergo significant scattering by current sheets as they propagate through the heliosphere. The higher occurrence rate of current sheets closer to the Sun (Liu et al., 2021; Lotekar et al., 2022) implies an even more pronounced impact on the transport of solar energetic particles.

These findings may have significant implications for the dynamics of energetic particles in both space and astrophysical plasmas. The extension of these scattering results to spatial transport—both parallel and perpendicular—is developed in Chapter 5. Efficient pitch-angle scattering enhances the ability of particles to reverse direction along magnetic field lines, thereby reducing their tendency to stream freely and limiting parallel transport. In quasi-linear theory, the parallel spatial diffusion coefficient is approximately inversely proportional to the pitch-angle diffusion coefficient for resonant interactions (Engelbrecht et al., 2022; Jokipii, 1966; 1968). Additionally, observations frequently reveal broad spatial distributions of solar energetic particles and the formation of particle reservoirs (Cohen et al., 2021), suggesting either reduced diffusion rates along magnetic field lines or highly efficient cross-field diffusion (Zhang et al., 2009). Our results indicate that the pitch-angle scattering due to current sheets can significantly affect parallel and perpendicular transport, and this point will be addressed in future work.

4.6 Data Availability

The code and data used for the findings and figures in this study are available at https://github.com/Beforerr/ion_scattering_by_SWD. ARTEMIS and Wind data are available at NASA’s Space Physics Data Facility (SPDF) <https://spdf.gsfc.nasa.gov>.

Chapter 5

Energetic Particle Transport Driven by Solar Wind Current Sheets

The transport of solar energetic particles (SEPs) through the heliosphere is governed by interactions with the turbulent interplanetary magnetic field (Effenberger et al., 2025; Engelbrecht et al., 2022; Klein & Dalla, 2017; Pucci et al., 2016). In the standard quasi-linear theory (QLT) framework (Jokipii, 1966; 1971), pitch-angle scattering arises from resonant interactions between particles and small-amplitude magnetic fluctuations ($\delta B/B_0 \ll 1$), yielding a pitch-angle diffusion coefficient $D_{\mu\mu}$ expressed as an integral over the turbulence power spectrum. The parallel diffusion coefficient follows as

$$\kappa_{\parallel} = \frac{v^2}{8} \int_{-1}^1 \frac{(1 - \mu^2)^2}{D_{\mu\mu}} d\mu$$

where $\mu = \cos \alpha$ is the pitch-angle cosine (Jokipii, 1966). Perpendicular transport is attributed to the field-line random walk (FLRW) combined with parallel scattering that decorrelates particles from their initial field lines (Matthaeus et al., 2003; Shalchi, 2009), with the nonlinear guiding center (NLGC) theory (Matthaeus et al., 2003) predicting a roughly constant ratio $\kappa_{\perp}/\kappa_{\parallel} \sim 2\%–4\%$, largely independent of particle energy (Shalchi, 2021).

Current sheets violate the assumptions underlying QLT: when the particle gyroradius becomes comparable to the sheet thickness, the scale separation assumed in QLT breaks down, the first adiabatic invariant is no longer conserved (Neishtadt, 2019; Tennyson et al., 1986), and scattering proceeds through geometrical chaotization of the quasi-adiabatic invariant I_z at separatrix crossings rather than through resonant diffusion—as quantified in Chapter 4 (Zhang et al., 2025b).

Current sheets also introduce a perpendicular transport channel absent from the FLRW framework. Near these structures, guiding-center theory is inapplicable: particles become demagnetized and may jump between magnetic field lines without any field-line wandering

(Malara et al., 2021; 2023; Qin & Li, 2008; Zelenyi et al., 2011). The efficiency of this cross-field transport is expected to depend strongly on particle energy, in contrast to the roughly energy-independent $\kappa_{\perp}/\kappa_{\parallel}$ ratio predicted by QLT-based models.

This chapter investigates both parallel and perpendicular transport of energetic particles driven by interactions with current sheets, extending the pitch-angle scattering analysis of Chapter 4 and building on prior work (Artemyev et al., 2020a; Malara et al., 2023; Zhang et al., 2025b). By incorporating statistical parameters derived from the multi-mission observational surveys of Chapter 2 and Chapter 3 into a force-free current sheet model, we analyze transport through an ensemble of current sheets and characterize the long-term diffusive behavior across a range of particle energies.

5.1 Current Sheet Model

Current sheets are meso-scale structures where the magnetic field direction changes significantly from one side to the other. In the solar wind, a large fraction of observed current sheets are approximately force-free, meaning that the magnetic pressure is roughly constant across the structure and the field rotates rather than compresses (Vasko et al., 2022). This force-free character has an important consequence for particle dynamics: the intermediate-variance magnetic field component peaks at the sheet center, producing a phase-space asymmetry that drives the superfast (geometrical) scattering mechanism discussed above.

We model current sheets using a 1D force-free magnetic field configuration where $\mathbf{B}$ depends only on the z coordinate (the normal direction):

$$\mathbf{B}(z) = B[\cos \theta \mathbf{e}_z + \sin \theta \sin \varphi(z) \mathbf{e}_x + \sin \theta \cos \varphi(z) \mathbf{e}_y]$$

In this configuration, the total magnetic magnitude B and the normal component $B_z = B \cos \theta$ remain constant, while the primary component B_x undergoes a reversal. The rotation angle is prescribed using a hyperbolic tangent profile $\phi(z) = \beta \tanh(z/L)$, where L is the half-thickness and β is the shear angle. The parameter θ controls the ratio of the normal component to the total field: a small θ corresponds to a nearly normal field (the

particle crosses the sheet quickly), while $\theta \rightarrow \pi/2$ corresponds to a nearly tangential field. The shear angle β determines the total rotation of the magnetic field across the sheet, with $\beta = \pi/2$ representing a full 180° reversal.

The configuration parameters (B , L , θ , and β) are drawn from statistical distributions obtained from solar wind observations (Zhang et al., 2026a) at 1 AU (ARTEMIS (Angelopoulos, 2011) and Wind (Acuña et al., 1995)) and at 0.1 AU (Parker Solar Probe (Fox et al., 2016)). The key parameter controlling the particle-sheet interaction is the ratio of the particle’s gyroradius ρ to the sheet thickness L . When $\rho/L \gtrsim 1$, the particle cannot complete a full gyration near the current sheet, the adiabatic invariant is violated, and significant scattering occurs.

5.2 Transport Model

We employ a Monte Carlo method with test-particle simulations to investigate transport through multiple current sheets. The approach proceeds in two stages: first, we characterize the outcome of individual particle–current sheet interactions; second, we chain these interactions together to build up macroscopic transport statistics.

5.2.1 Individual Particle–Current Sheet Interaction

For each interaction, we numerically solve the Newton-Lorentz equation $d\mathbf{p}/dt = q\mathbf{v} \times \mathbf{B}$, neglecting large-scale electric fields and explicit time dependence, as energetic particle velocities ($v \gg v_A$) justify the static field approximation. The particle is launched far from the sheet center with a random gyrophase $\psi \in [0, 2\pi)$ and traced until it exits the interaction region. Magnetic field parameters for each interaction (B , L , θ , β) are randomly sampled from the observed distributions.

From each interaction we extract two quantities:

1. **Pitch-angle change $\Delta\alpha$.** We record the pitch angle $\alpha = \arccos(v_{\parallel}/v)$ at entry and exit. Depending on the ratio ρ/L and the specific field configuration, $\Delta\alpha$ can range from negligibly small (when $\rho/L \ll 1$ and the interaction is adiabatic) to order unity (when

$\rho/L \gtrsim 1$ and geometrical chaotization occurs). Large pitch-angle jumps can reverse the particle's direction of motion along the field, i.e., cause reflection.

2. **Perpendicular guiding-center displacement $\Delta \mathbf{r}_\perp$.** We compute the guiding-center position at entry and exit and take the difference projected perpendicular to the background magnetic field. Figure 5.1 illustrates this measurement for an example trajectory: a particle approaches the current sheet gyrating along its initial field line (green), interacts with the sheet and becomes temporarily demagnetized, and exits gyrating along a different field line (pink). The perpendicular displacement $\Delta \mathbf{r}_\perp$ represents the net jump between field lines—a cross-field transport that occurs without any field-line random walk. This mechanism is distinct from the FLRW-based perpendicular transport assumed in quasi-linear models: here, the particle physically decouples from its original field line during the demagnetized phase and reattaches to a neighboring one.

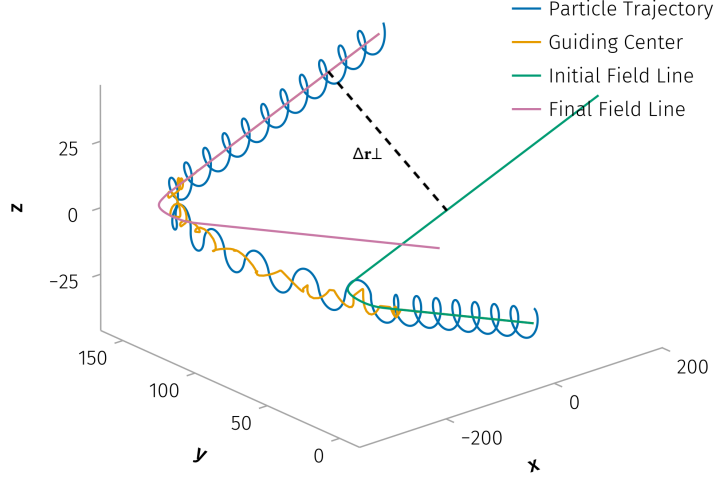


Figure 5.1: Example trajectory of a particle interacting with a current sheet. Blue: full particle trajectory; Orange: guiding-center trajectory; Green: initial magnetic field line; Pink: final magnetic field line. The perpendicular guiding-center displacement $\Delta \mathbf{r}_\perp$ is the separation between the initial and final field lines, representing a cross-field jump that occurs through demagnetization rather than field-line random walk.

We also estimate the trapping time within the current sheet by subtracting the ballistic transit time (the time the particle would take to traverse the sheet in the absence of scat-

tering) from the total simulation time. For most interactions where significant scattering occurs, the particle remains trapped within the sheet for several gyroperiods, executing multiple bounces across the field reversal before escaping.

5.2.2 Accumulation Across Multiple Current Sheets

To model transport through the heliosphere, we chain together a sequence of current sheet interactions separated by free-streaming intervals. Each particle is initialized with a random pitch angle α and gyrophase ψ . Between successive current sheets, the particle traverses a distance d corresponding to the observed mean spatial separation between neighboring sheets. For simplicity, we assume (1) the current sheets are static during the interaction time; (2) d is a constant depending only on the heliocentric radial distance; and (3) there is no pitch-angle scattering during transit. The transit time between sheets is $t_d = d / |v_{\parallel}|$.

The total parallel displacement after N interactions accumulates as

$$\Delta z = \sum_i \text{sgn}(\cos \alpha_i) \cdot d$$

where α_i is the pitch angle after the i -th interaction. This expression reflects the fact that the particle streams along the field line between sheets, with the sign determined by the direction of parallel motion.

The perpendicular displacement requires more careful treatment. In the heliosphere, the local magnetic field direction rotates with respect to the large-scale geometry—in particular, the radial direction—as the field follows the Parker spiral. Consequently, the perpendicular displacement acquired at one current sheet is oriented differently in the heliospheric frame from the displacement acquired at a distant sheet. We account for this slowly varying field-line orientation between current sheets by applying a random rotation $\mathbf{R}_i$ to each individual displacement, so that the accumulated perpendicular displacement is

$$\Delta \mathbf{r}_{\perp} = \sum_i \mathbf{R}_i \cdot \Delta \mathbf{r}_{\perp,i}$$

where $\Delta \mathbf{r}_{\perp,i}$ is the perpendicular displacement from the i -th interaction.

This scheme captures the essential physics while remaining computationally tractable: the expensive part (solving the Newton-Lorentz equation within each current sheet) is performed once per interaction, while the free-streaming intervals between sheets are handled analytically.

5.3 Results

We propagate an ensemble of 512 particles and compute the mean-square displacements $\langle \Delta z^2 \rangle$ and $\langle \Delta \mathbf{r}_{\perp}^2 \rangle$ by interpolating trajectories at successive time steps. Both parallel and perpendicular mean-square displacements grow linearly with time in the asymptotic limit, confirming diffusive behavior. The diffusion coefficients are extracted from the late-time behavior:

$$D_{\parallel} = \lim_{t \rightarrow \infty} \langle \Delta z(t)^2 \rangle / 2t, \quad D_{\perp} = \lim_{t \rightarrow \infty} \langle \Delta \mathbf{r}_{\perp}(t)^2 \rangle / 2t$$

evaluated at $t = 2 \times 10^3$ s, by which time the ensemble has undergone sufficiently many current sheet interactions for the transport to reach the diffusive regime.

Figure 5.2 displays state trajectories—parallel displacement and perpendicular displacement as functions of time—for an ensemble of 1-MeV particles interacting with near-Earth current sheets.

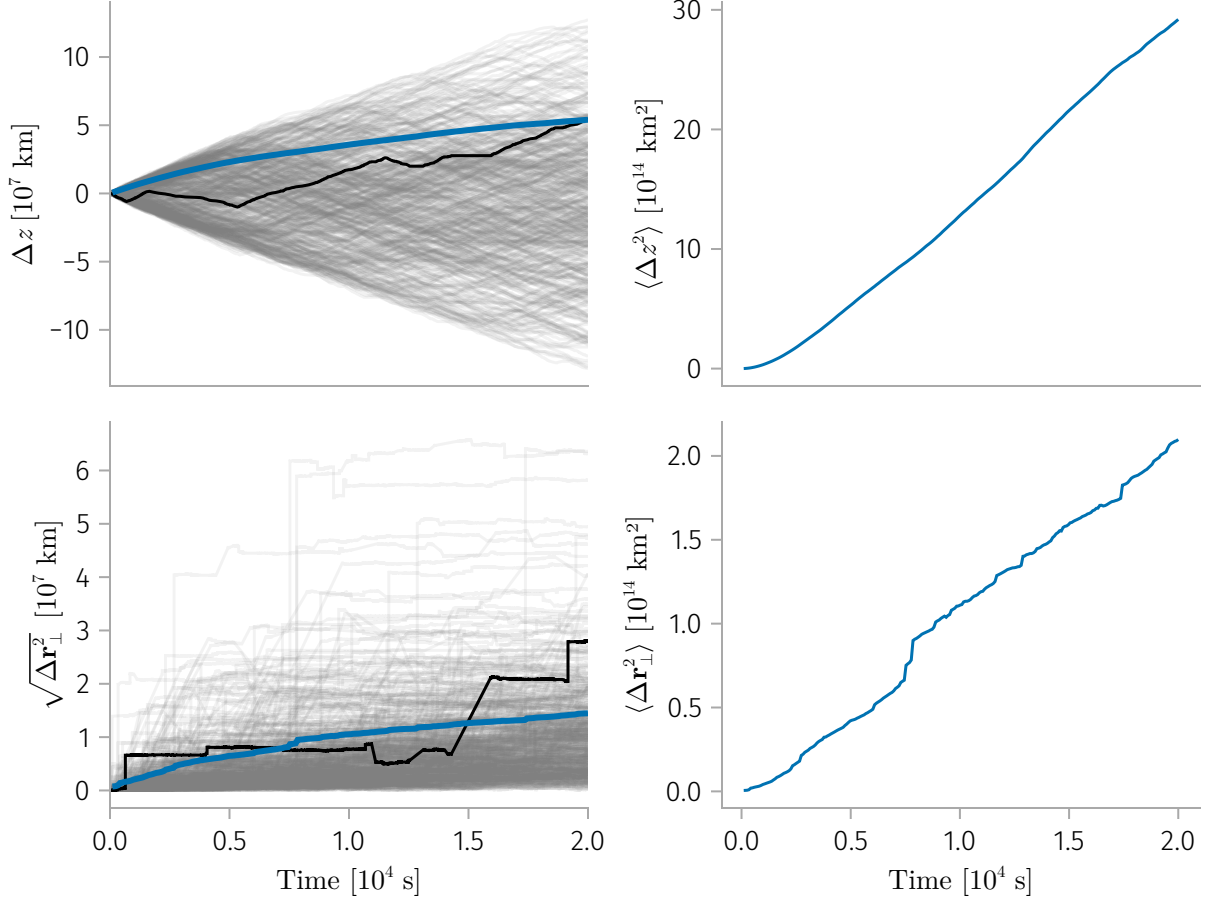


Figure 5.2: Parallel and perpendicular displacements for 1-MeV particles interacting with near-Earth current sheets. Gray lines: individual particle trajectories; Blue line: standard deviation of the ensemble; Black line: a representative trajectory.

Several features of the trajectories merit discussion. The parallel displacement (left panel) grows approximately linearly with time for most particles, reflecting steady streaming along the magnetic field. However, occasional particles undergo abrupt direction reversals—visible as sharp kinks in the trajectory—where a single current sheet interaction produces a pitch-angle jump large enough to reverse the sign of $v_{\parallel}$. These reflection events are a hallmark of the superfast scattering mechanism: in the quasi-linear picture, pitch-angle changes are small and incremental, so direction reversals require the cumulative effect of many scattering events, whereas current sheet interactions can produce them in a single step.

The perpendicular displacement (right panel) shows a qualitatively different character. Most of the time, the perpendicular position changes very little between current sheet

encounters (consistent with our assumption of no cross-field transport during free streaming). At each current sheet interaction, however, the particle may undergo a discrete perpendicular jump $\Delta \mathbf{r}_{\perp,i}$. The magnitude of these jumps varies widely: some interactions produce negligible cross-field displacement (when the particle remains magnetized throughout), while others produce jumps comparable to the gyroradius (when the particle becomes demagnetized, as illustrated in Figure 5.1). The stochastic accumulation of these discrete jumps—each randomly oriented due to the random rotation—produces a random walk that is macroscopically diffusive.

It is important to note that while individual interactions can produce large, non-diffusive jumps in both pitch angle and perpendicular position, the ensemble-averaged transport is diffusive in the long-time limit. This is because the jumps are statistically independent (each current sheet has randomly sampled parameters) and their accumulation satisfies the central limit theorem. The diffusion coefficients $D_{\parallel}$ and $D_{\perp}$ thus provide a valid characterization of the macroscopic transport, even though the microscopic scattering mechanism is fundamentally non-diffusive.

Figure 5.3 summarizes the diffusion coefficients as functions of particle energy for 1 AU and 0.1 AU environments, comparing our results with quasi-linear theory predictions derived from measured magnetic turbulence power spectra (Chen et al., 2024).

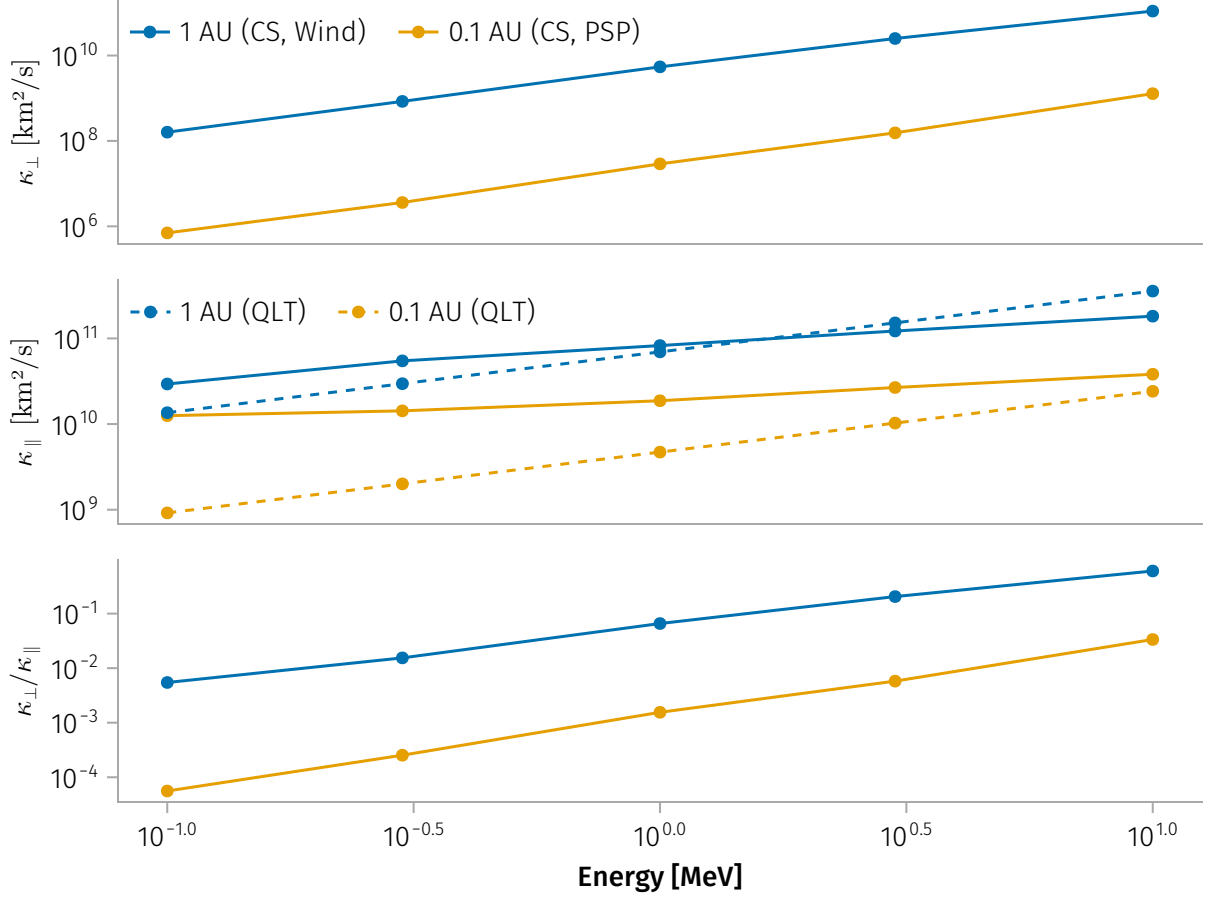


Figure 5.3: Diffusion coefficients vs.~particle energy at 1 AU and 0.1 AU. (a) Parallel diffusion; (b) Perpendicular diffusion; (c) Ratio of perpendicular to parallel diffusion.

The parallel diffusion coefficient ($D_{\parallel}$, panel a) increases with particle energy at both heliocentric distances. At 1 AU, the current-sheet-driven $D_{\parallel}$ is comparable in magnitude to the QLT prediction at low energies but diverges at higher energies. As particle energy increases, the gyroradius grows relative to the sheet thickness, so that a larger fraction of current sheets satisfies the condition $\rho/L \gtrsim 1$ for strong scattering. The pitch-angle scattering rate therefore increases with energy, though it may saturate once the gyroradius exceeds the thickness of most sheets. Nevertheless, $D_{\parallel}$ increases with energy because the particle velocity grows faster than the scattering rate, yielding a mean free path that increases with energy.

The perpendicular diffusion coefficient ($D_{\perp}$, panel b) shows a steeper energy dependence than $D_{\parallel}$. This arises because higher-energy particles, when they do interact strongly with a current sheet, undergo larger perpendicular displacements: the demagnetized gyroradius

sets the scale of the cross-field jump, and this scale grows with particle energy. The combination of fewer but larger perpendicular jumps produces a net $D_{\perp}$ that increases rapidly with energy.

The most significant result is the energy dependence of the ratio $D_{\perp}/D_{\parallel}$ (panel c). In contrast to the QLT-based prediction of a roughly constant ratio of 2%–4%, our simulations show that $D_{\perp}/D_{\parallel}$ increases with particle energy, exceeding the typically assumed range for particles above ~ 1 MeV at 1 AU. This strong energy dependence arises from the distinct scalings of the two transport channels. Parallel diffusion scales as $D_{\parallel} \sim v^2/\nu$, where the scattering rate ν increases with energy but is outpaced by the velocity dependence. Perpendicular diffusion benefits additionally from the growth of the cross-field jump size with the demagnetized gyroradius, giving $D_{\perp}$ a steeper energy scaling than $D_{\parallel}$ and producing a ratio that is far from constant.

This result differs from earlier studies suggesting the ratio is largely independent of energy (Shalchi, 2021). It is also consistent with the finding of (Pucci et al., 2016) that intermittency influences parallel transport, and extends it by demonstrating that current sheets—a primary source of intermittency—also strongly affect perpendicular transport. Our findings offer a potential explanation for observational puzzles such as the large longitudinal and latitudinal extent of solar energetic particle (SEP) events detected by widely separated spacecraft (Desai & Giacalone, 2016; Lario et al., 2014; Zhang et al., 2009). If perpendicular diffusion is substantially more efficient at high energies than previously assumed, the broad spatial distributions of SEPs may be a natural consequence of current-sheet-mediated cross-field transport rather than requiring extended coronal injection or other non-standard mechanisms.

5.4 Summary and Discussion

This study demonstrates that interactions with current sheets are a significant driver of energetic-particle transport in the heliosphere. By combining observed current sheet statistics with test-particle simulations, we have shown that:

1. Current sheet interactions produce both parallel transport (through pitch-angle scattering and reflection) and perpendicular transport (through cross-field jumps during demagnetization). Both transport channels operate through mechanisms that are qualitatively distinct from those assumed in quasi-linear theory.
2. The perpendicular-to-parallel diffusion ratio $D_{\perp}/D_{\parallel}$ is not constant but increases with particle energy, exceeding the typically assumed 2%–4% for particles above ~ 1 MeV at 1 AU. This energy dependence may be attributed to the perpendicular jump size scaling with the demagnetized gyroradius.
3. The current-sheet-driven transport is quantitatively significant: the diffusion coefficients are comparable to or exceed QLT predictions at energies where the gyroradius–thickness resonance condition is well satisfied.

Our model is necessarily simplified and several important effects have been neglected. First, we do not include realistic waiting-time distributions between current sheets. The observed solar wind exhibits clustered distributions of discontinuities (Borovsky, 2010), and heavy-tailed waiting-time distributions could give rise to anomalous (non-Fickian) transport regimes (Effenberger et al., 2025; Giacalone et al., 2022), where the mean-square displacement grows as t^{α} with $\alpha \neq 1$. Our use of a fixed inter-sheet spacing d precludes this possibility and may underestimate the variability of transport in the real solar wind.

Second, we neglect the systematic evolution of the heliospheric magnetic field with radial distance and the resulting changes in current-sheet configurations experienced by propagating particles. As particles travel from the Sun to 1 AU, they encounter current sheets whose statistical properties (thickness, shear angle, field strength) evolve with heliocentric distance. A self-consistent treatment would couple the transport model to a radial profile of current sheet statistics.

Third, the heliosphere is inherently three-dimensional (Effenberger & Litvinenko, 2014), and actual current sheets exhibit complex three-dimensional structures—including reconnection sites, flux ropes, and plasmoid chains (Pezzi et al., 2021) — that are not captured in our one-dimensional force-free model. These structures may introduce additional scattering channels and modify the perpendicular transport efficiency.

Despite these simplifications, our results provide some of the first quantitative evidence that current sheets play a substantial role in modulating energetic-particle transport. Because current sheets constitute a major component of solar-wind turbulence (Malandraki et al., 2019) and contribute significantly to magnetic field fluctuations (Borovsky, 2010), accounting for their effects is essential for developing accurate transport models (Whitman et al., 2023). The strong energy dependence of the perpendicular-to-parallel diffusion ratio, in particular, may have important implications for interpreting multi-spacecraft SEP observations and for forecasting radiation environments in the inner heliosphere. Future work should aim to incorporate more realistic descriptions of current-sheet geometries, dynamics, and spatial distributions to better quantify and constrain their influence on particle propagation. A broader discussion of open questions and future directions is provided in Chapter 6.

Chapter 6

Summary and Future Perspectives

6.1 Research Summary

The central scientific contribution of this thesis is a quantitative, observation-informed account of how kinetic-scale solar wind current sheets scatter energetic particles and shape their transport through the inner heliosphere. This is achieved through two interconnected programs—one observational (Chapter 2 and Chapter 3), one theoretical and numerical (Chapter 4 and Chapter 5)—whose results build on and reinforce each other directly.

Observational characterization across the inner heliosphere. The first program establishes how current sheet properties vary across heliocentric distances using simultaneous multi-spacecraft measurements. In the inner heliosphere study (Chapter 5), we analyzed three Parker Solar Probe encounter intervals (Encounters 7–9), selected for their contrasting geometric alignments with near-Earth spacecraft ARTEMIS and WIND, allowing us to distinguish spatial evolution from temporal or solar-cycle variability. Using a robust automated detection algorithm applied consistently across all missions, we identified and characterized more than 45,000 current sheets. The use of normalized, resolution-independent detection criteria—moving beyond earlier fixed-threshold approaches—enables meaningful cross-mission comparison.

The central observational finding is that the majority of solar wind current sheets are kinetic-scale structures across the inner heliosphere and their normalized properties are largely invariant across radial distance. While absolute thickness increases and absolute current density decreases as the solar wind expands, both quantities remain nearly constant when normalized to the local ion inertial length d_i and Alfvén current density J_A respectively—from 0.17 AU (PSP near perihelion) out to 1 AU. The normalized current density, with most probable value around 0.05–0.15 J_A , and normalized thickness,

centered around $2\text{--}4\ d_i$, show distributions whose widths greatly exceed any systematic radial trend, indicating that the intrinsic spread of current sheet properties dominates over the evolution. A pronounced inverse correlation between current density and spatial scale—stronger currents in thinner sheets—extends over nearly two additional orders of magnitude compared to prior studies, establishing this as a universal feature of solar wind turbulence across kinetic to MHD scales. The Alfvénicity of current sheets, quantified through the Sonnerup parameter $Q^\pm$, is found to be primarily controlled not by the sheet’s own properties (thickness, current density, plasma β) but by the surrounding turbulent environment—specifically the cross helicity σ_c and residual energy σ_r of the ambient solar wind. This demonstrates that current sheets are embedded within, and shaped by, the local turbulent cascade rather than being independent structures.

The outer heliosphere study (Chapter 4) extends this characterization from 1 to 5 AU using the Juno spacecraft during its cruise phase (2011–2016), complemented by simultaneous 1 AU observations from WIND, ARTEMIS, and STEREO. More than 130,000 current sheet intervals were identified. The occurrence rate decreases with heliocentric distance following an approximate $1/r$ law—from roughly 150 events per day near 1 AU to ~ 30 per day near 5 AU. Through a geometric model accounting for the expanding spherical shell and the Parker spiral orientation of current sheet normals, we show that this apparent decrease may be largely a geometric effect: when the global occurrence rate is corrected for the fractional cross-sectional coverage of a planar structure at distance r , the factor of 5 decrease in local occurrence rate reduces to a factor of only ~ 1.3 , with the residual attributable to physical annihilation processes such as magnetic reconnection. The normalized thickness and current density continue to remain nearly constant from 1 to 5 AU, confirming that current sheets maintain their kinetic character throughout the outer inner heliosphere and that the characteristic velocity $\tilde{v}_B \propto BL$ is approximately radially invariant—with direct implications for particle scattering efficiency.

Quantitative modeling of particle scattering and transport. The second program translates these observational constraints into a physics-based model of energetic particle scattering and transport. Chapter 6 develops an exact Hamiltonian formulation for a force-free, one-dimensional current sheet—retaining the full unexpanded magnetic vector potential rather than relying on Taylor expansions near the sheet center—and uses it to

conduct extensive test-particle simulations parameterized by the observed distributions of θ , ω_{in} , and $\tilde{v}_B$ from the 1 AU current sheet catalog of $\sim 100,000$ events.

The scattering outcome of each particle–sheet interaction is captured in a transition matrix (TM) mapping initial to final pitch angle $\alpha_0 \rightarrow \alpha_1$, averaged over the gyrophase. A central result is that for certain current sheets and particle energies, the TM combines a bright diagonal (weakly scattered particles) with off-diagonal structure representing large, non-diffusive pitch-angle jumps. The character of the scattering depends strongly on the shear half-angle β and the ratio v_p/v_B . Large β (large rotation angle) and $v_p \sim v_B$ (gyroradius comparable to sheet thickness) produce enhanced diffusion and particle reflection; very high energies ($v_p \gg v_B$) result in weak scattering over a narrow pitch-angle range. The uncertainty curve length $L_{uc}/\sqrt{H}$, which governs the probability of separatrix crossing, increases with both β and particle energy—confirming that the geometric chaotization mechanism is more pronounced for larger field rotations and higher-energy particles interacting with current sheets of comparable scale.

A statistically weighted transition matrix (WTM) is constructed by averaging individual TMs over the observed distribution of current sheet properties at 1 AU. For 100 keV protons, the WTM shows a strong diagonal (most encounters produce little scattering) but with significant probability of both diffusive spreading and rare, large-angle jumps—a non-Markovian structure that cannot be reduced to a single diffusion coefficient. The long-term pitch-angle evolution is simulated through the iterative mapping $\alpha_{n+1} = W_{\Pi}(\alpha_n, \xi_n)$, where ξ_n is a uniformly sampled random variable encoding the gyrophase randomization. This produces pitch-angle histories characterized by infrequent but substantial jumps—exactly the non-Brownian dynamics anticipated from the intermittent distribution of current sheets. An effective pitch-angle diffusion rate $D_{\mu\mu}$ is extracted by fitting the second moment $M_2(n)$ of the pitch-angle distribution to a saturating exponential, and converted to a physical timescale $\mathcal{D}_{\mu\mu}$ using the observed current sheet occurrence rate and mean solar wind speed.

Chapter 7 extends this framework to spatial transport. Using a Monte Carlo approach in which particles traverse fixed separations d between successive current sheet encounters—drawn from the observed spacing distribution—and undergo scattering according to

the WTM, we compute both parallel displacement $\langle \Delta z^2 \rangle$ and perpendicular displacement $\langle \Delta \mathbf{r}_\perp^2 \rangle$ as functions of time for particle energies from 100 keV to 1 MeV. Both exhibit asymptotically diffusive behavior, with coefficients $D_\parallel$ and $D_\perp$ extracted from the linear growth of mean-square displacement at late times. A key finding is that the perpendicular diffusion coefficient $D_\perp$ scales more steeply with particle energy than $D_\parallel$, causing the ratio $D_\perp/D_\parallel$ to increase with energy and to exceed standard predictions from turbulent wave models at high energies. This arises because the perpendicular guiding-center displacement at each current sheet crossing—produced by demagnetization when the gyroradius is comparable to the sheet thickness—grows rapidly with particle energy, while the parallel transport is regulated by the pitch-angle scattering rate in a more gradual fashion. Furthermore, the characteristic velocity $\tilde{v}_B \propto BL$ is nearly radially invariant (confirmed by the observational results of Chapters 4–5), implying that the scattering efficiency—and thus both $D_\parallel$ and $D_\perp$ —remains significant throughout the inner heliosphere, with the higher occurrence rates closer to the Sun amplifying the effect further.

Taken together, these results establish current sheets as systematic, quantifiable agents of energetic particle scattering throughout the inner heliosphere. The observational invariance of normalized current sheet properties across 0.1–5 AU provides the empirical foundation; the Hamiltonian framework and test-particle simulations provide the physical mechanism and transport coefficients; and the non-Brownian, large-jump character of the scattering offers a natural explanation for the anomalous transport behavior—broad particle reservoirs, rapid longitudinal spreading—that has long challenged purely wave-based models of SEP propagation.

6.2 Opportunities for Future Research

The results of this thesis open several directions for future investigation:

Origins and evolution of solar wind current sheets. A fundamental question left open by this thesis is the origin of the current sheet population we characterize. The observational invariance of normalized current sheet properties across 0.1–5 AU is consistent with two competing pictures: structures generated near the Sun (potentially

by turbulence there) and convected outward in a way that evolves consistently with local plasma properties, and structures generated locally and continuously by turbulence throughout the heliosphere. One way to distinguishing is tracking the propagation velocity. Liu et al. (2021) showed that outward-propagating rotational discontinuities have velocities scaling as r^{-1} —consistent with Alfvénic advection—while a minority propagate inward, suggesting local turbulent generation. A more systematic investigation of propagation velocities as a function of heliocentric distance, spatial scale, and solar wind type and current sheet character (RD or TD) would help quantify the relative contributions of solar-origin and locally-generated sheets. If multiple mechanisms is possible, Closely related is the question of what fraction of the current sheet population arises from the steepening of large-amplitude Alfvén waves versus direct turbulent cascade. A statistical decomposition of the current sheet population by generation mechanism would provide critical insights.

Curvature, reversal-scale statistics and connections to the broader intermittency picture. The quasi-adiabatic framework developed here treats scattering in terms of the internal magnetic field structure of individual current sheets. A complementary perspective, developed by Lemoine (2023) and Kempfski et al. (2023), frames scattering as a consequence of regions where the field-line curvature radius κ^{-1} or perpendicular reversal scale drops below the particle gyroradius—a condition met whenever the turbulence is sufficiently intermittent on scales $l \sim r_g$. This curvature-based picture is broader than the current sheet picture: sharp bends of the magnetic field, whether or not they constitute a recognized current sheet, can produce order-unity changes in the magnetic moment. However, as explored in several theoretical works (Artemyev et al., 2013a; 2014; 2020a), the internal structure containing this curvature matters for the scattering outcome—superfast or otherwise—depending on the symmetry of the Hamiltonian, specifically the existence and complexity of normal and guide field components. Unifying these perspectives requires progress on several fronts. First, the curvature statistics of the solar wind are beginning to be characterized observationally (Hu et al., 2025), but the perpendicular reversal-scale statistics—which Kempfski et al. (2023) show act as a gatekeeper for energy-dependent scattering in the fold-propagation model—remain unmeasured. Determining whether the power-law tails of the curvature PDF are dominated by current sheet crossings, by smaller-scale bends within flux tubes, or by some combination would clarify the relationship between the current-sheet-specific scattering model developed here and the more general,

structure-agnostic turbulent scattering framework. Second, the contribution of small-scale magnetic mirrors and their interplay with curvature deserves further investigation: as Lemoine (2023) notes, the mirror term $m \equiv B^{-1} \hat{\mathbf{b}} \cdot (\hat{\mathbf{b}} \cdot \nabla) B$ and the curvature κ are likely correlated along field lines—both are large at current sheets—yet their joint influence on particle scattering has not been quantified. Third, the results of both Lemoine (2023) and Kempfski et al. (2023) apply in the limit of large-amplitude turbulence with no or weak mean field, whereas the solar wind spans a range of conditions of $\delta B/B_0$. A systematic study of how the curvature PDFs and fold statistics evolve as $\delta B/B_0$ decreases toward unity is essential for assessing the relevance of these models to SEP transport. Such a synthesis would allow the scattering framework developed in this thesis to be embedded within, and validated against, a broader theory of intermittency-mediated transport.

Non-diffusive transport and beyond the Fokker–Planck framework. Perhaps the most theoretically significant open problem raised by this thesis is how to properly model the non-diffusive microphysics of current-sheet-induced scattering within a macroscopic transport framework. The pitch-angle and spatial evolution we find is intermittent: long periods of near-free-streaming punctuated by rare but violent jumps. This statistical structure—heavy-tailed jump distributions rather than frequent small deflections—fundamentally violates the Markovian, continuous-scattering assumption of the Fokker–Planck equation (Zimbardo & Perri, 2020), and can give rise to anomalous transport: subdiffusive when current sheets trap particles, superdiffusive when intense encounters produce large displacements. The effective $D_{\mu\mu}$ derived in Chapter 4 provides a useful first approximation, but its validity as a single parameter characterizing such a heavy-tailed process needs careful assessment, particularly in the energy range where gyro-radii are comparable to typical sheet thicknesses and large pitch-angle jumps are frequent. Several alternative frameworks deserve systematic exploration. Fractional diffusion models (del-Castillo-Negrete et al., 2005) and Lévy-walk statistics (Zaburdaev et al., 2015) can naturally accommodate the power-law jump distributions. A complementary approach, inspired by Ewart et al. (2025), treats the solar wind as a multiphase diffusive medium in which different plasma types (Xu & Borovsky, 2015) host statistically distinct current sheet populations with different scattering properties and substantially different diffusion coefficients. In that framework, the energy dependence of transport is modified by the multiphase structure only when there is a moderate level of perpendicular cross-field

diffusion—a condition that our results suggest is met for SEPs interacting with current sheets in the 100 keV to 1 MeV range. Applying this picture to the solar wind requires characterizing the spatial distribution of plasma types and the current sheet populations embedded within each.

Beyond one-dimensional force-free current sheets. The magnetic field model used throughout this thesis is a force-free configuration in which the field rotates along one dimension. This captures the essential physics of non-adiabatic scattering—separatrix crossings, geometric jumps, and the role of the shear angle β —but it necessarily omits several features of real solar wind current sheets. First, the internal structure of many observed sheets is genuinely multi-dimensional: the guide field, the normal component, and the B_m peak can all vary along the sheet surface, and plasma density and temperature gradients can contribute forces that modify the field profile away from the force-free limit. Second, other coherent structures—Alfvén vortices, magnetic holes, flux ropes, and compressive structures—are present in the solar wind alongside current sheets and may contribute independently to particle scattering through distinct mechanisms. The curvature-scattering framework of Lemoine (2023) already partially addresses this by treating the full curvature field rather than isolated current sheets, but a comprehensive characterization of the scattering contribution from each structure type, as a function of particle energy and structure geometry, remains to be developed. Test-particle simulations in more realistic field configurations would be a productive next step toward a complete, structure-resolved model of SEP transport in the turbulent inner heliosphere.

Appendix A

Multifluid Equilibrium Model of Current Sheets With Interpenetrating Ion Beams

Solar wind discontinuities are localized, transient, intense coherent structures widely observed in the heliosphere (Greco et al., 2016; Podesta, 2017; Vasko et al., 2022; Vasquez et al., 2007; Zhang et al., 2025a). They exhibit Alfvén-wave-like character, as evidenced by strong correlations between fluctuations of plasma velocity and Alfvén velocity (Artemyev et al., 2019b; D'Amicis et al., 2021; De Keyser et al., 1998; Paschmann et al., 2013). Theoretical models predict that such discontinuities may originate from nonlinear Alfvén-wave evolution (Medvedev et al., 1997; Medvedev & Diamond, 1996) or plasma turbulence (Servidio et al., 2011). Their magnetic structure is often best described as a current sheet with approximately constant magnetic-field magnitude B and a strong rotation of the field direction (Neukirch et al., 2020b). Being quasi-one-dimensional structures, these current sheets contain two main magnetic-field components: $B_x(z)$ reversing sign across the sheet, and $B_y(z)$ reaching a local maximum near the B_x reversal, where z denotes the coordinate along the current-sheet normal. This configuration is important for magnetic reconnection and energetic-particle scattering (Artemyev et al., 2020a; Malara et al., 2021; 2023; Shi et al., 2021; Zhang et al., 2025b).

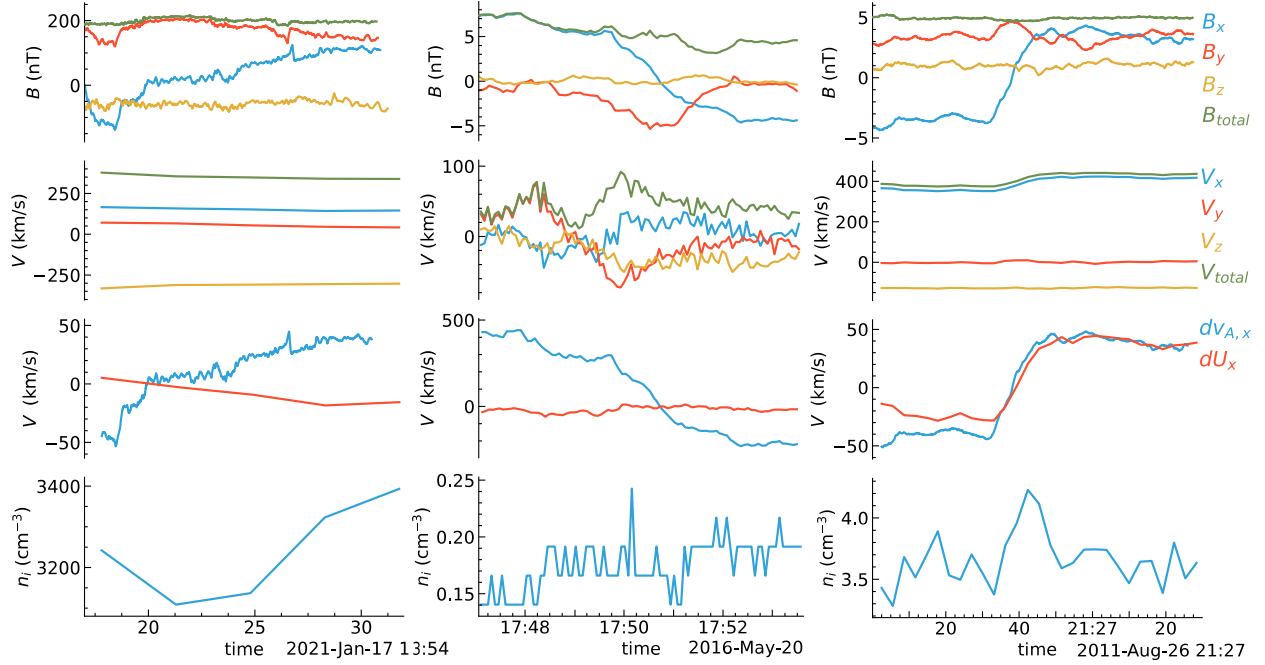


Figure A.1: Three examples of current sheets (discontinuities) observed by the Parker Solar Probe (PSP) (Fox et al., 2016), ARTEMIS (Angelopoulos, 2011), and Wind (Acuña et al., 1995) spacecraft in the **lmn** coordinate system, each with sub-Alfvénic velocity jumps. Here **l** $\equiv x$ represents the maximum variance direction, **m** $\equiv y$ the intermediate variance direction, and **n** $\equiv z$ the minimum variance direction. From top to bottom, the panels display magnetic-field components, plasma velocity, shifted Alfvén velocity in the x -direction, shifted plasma velocity, and plasma density. Details about instruments and data sets are provided in the Appendix.

Figure A.1 presents three examples of current sheets observed in the solar wind and at Earth’s distant magnetotail. Each shows a B_x reversal paired with a B_y peak that compensates the loss in magnetic pressure $B_x^2/2\mu_0$, with typical half-widths $L \sim 1\text{--}20d_i$ ($d_i \approx 100$ km at 1 AU and ≈ 10 km near the Sun (Zhang et al., 2026a)). Several models describe current sheets with $B = \text{const}$ and $B_z = 0$, where the configuration resembles a tangential discontinuity (Harrison & Neukirch, 2009; Neukirch et al., 2020b). However, when $B_z \neq 0$, tangential-discontinuity models are no longer sufficient and an additional stress balance must hold beyond the pressure balance $B_x^2 + B_y^2 + 2\mu_0 P_\perp = \text{const}$ (Hudson, 1970). In ideal single-fluid MHD this additional condition is $|\Delta \mathbf{V}_A| = |\Delta \mathbf{U}|$, where Δ denotes the change across the sheet, $\mathbf{V}_A \equiv \mathbf{B}/\sqrt{\mu_0 \rho}$ is the Alfvén velocity, and $\mathbf{U}$ is the plasma bulk velocity.

Spacecraft observations show that the Alfvénicity, defined here as $|\Delta \mathbf{U}|/|\Delta \mathbf{V}_A|$, is frequently below unity in current sheets (see Figure A.1 and (Artemyev et al., 2019b; De Keyser et al., 1998; Paschmann et al., 2013)). One important generalization is therefore a multi-component plasma. Spacecraft observations frequently reveal counter-streaming ion populations in and around solar-wind current sheets (Artemyev et al., 2020b; Shen et al., 2024), and such interpenetrating beams can significantly modify stress balance and internal structure (Vasko et al., 2014). These kinetic features, including the partitioning between thermal and drift energy and the distinct dynamics of each ion population, cannot be captured by single-fluid models.

Following (Shi et al., 2021; Steinhauer et al., 2008), this appendix develops a multifluid model for 1D current sheets with $B_z \neq 0$. We extend that framework by including a shear (guide) magnetic field B_y and gyrotropic pressure anisotropy, and we derive explicitly how the density contrast between counter-streaming ion beams controls the Alfvénicity of the current sheet. A fully kinetic treatment is more complete but difficult to solve analytically when $B_z \neq 0$; the multifluid approach remains analytically tractable while retaining key multi-species effects.

A.1 Multifluid Model

We assume that the asymptotic boundary conditions are known, including the normal magnetic field B_z , magnetic-field magnitude B , and properties of incident fluid streams. The governing equations for a collisionless multifluid plasma are

$$\left(\frac{\partial}{\partial t} + \mathbf{u}_\alpha \cdot \nabla\right)n_\alpha = -n_\alpha \nabla \cdot \mathbf{u}_\alpha \quad (8)$$

$$m_\alpha n_\alpha \left(\frac{\partial}{\partial t} + \mathbf{u}_\alpha \cdot \nabla\right)\mathbf{u}_\alpha = -\nabla \cdot \mathbf{P}_\alpha + q_\alpha n_\alpha (\mathbf{E} + \mathbf{u}_\alpha \times \mathbf{B}) \quad (9)$$

$$\nabla \times \mathbf{B} = \mu_0 \left(\mathbf{J} + \epsilon_0 \frac{\partial \mathbf{E}}{\partial t}\right) \quad (10)$$

$$\nabla \cdot \mathbf{B} = 0. \quad (11)$$

Here α indicates species, n_α number density, m_α mass, q_α charge, $\mathbf{u}_\alpha$ bulk velocity, $\mathbf{P}_\alpha$ pressure tensor, $\mathbf{E}$ electric field, $\mathbf{B}$ magnetic field, $\mathbf{J}$ current density, ϵ_0 vacuum permittivity, and μ_0 vacuum permeability.

We seek steady-state solutions in the deHoffmann-Teller frame, with $\partial/\partial t = 0$, and assume all variables vary only along z . Conservation of mass integrates to $\Gamma_\alpha \equiv n_\alpha u_{\alpha z} = \text{const}$, and Gauss's law requires constant B_z . Steady Faraday's law fixes E_x and E_y as constants, which vanish in the deHoffmann-Teller frame, leaving $\mathbf{E} = -(d\varphi/dz)\hat{\mathbf{z}}$. The steady momentum equations are

$$m_\alpha \Gamma_\alpha \frac{du_{\alpha x}}{dz} = -\frac{dP_{xz,\alpha}}{dz} + q_\alpha (n_\alpha u_{\alpha y} B_z - \Gamma_\alpha B_y) \quad (12)$$

$$m_\alpha \Gamma_\alpha \frac{du_{\alpha y}}{dz} = -\frac{dP_{yz,\alpha}}{dz} + q_\alpha (\Gamma_\alpha B_x - n_\alpha u_{\alpha x} B_z) \quad (13)$$

$$m_\alpha \Gamma_\alpha \frac{du_{\alpha z}}{dz} = -\frac{dP_{zz,\alpha}}{dz} + n_\alpha q_\alpha \left(-\frac{d\varphi}{dz} + u_{\alpha x} B_y - u_{\alpha y} B_x\right) \quad (14)$$

Ampere's law gives

$$1/\mu_0 \frac{dB_y}{dz} = -J_x = -\sum_\alpha q_\alpha n_\alpha u_{\alpha x} \quad (15)$$

$$1/\mu_0 \frac{dB_x}{dz} = J_y = \sum_\alpha q_\alpha n_\alpha u_{\alpha y} \quad (16)$$

$$0 = J_z = \sum_\alpha q_\alpha n_\alpha u_{\alpha z} = \sum_\alpha q_\alpha \Gamma_\alpha. \quad (17)$$

Far from the current sheet all derivatives vanish. Equation 13 then reduces to

$$\Gamma_\alpha B_{x(\pm\infty)} - n_{\alpha(\pm\infty)} u_{\alpha x} (\pm\infty) B_z = 0. \quad (18)$$

Introducing $U_x \equiv \sum_{\alpha} m_{\alpha} n_{\alpha} u_{\alpha x} / \rho$, $V_{A,x} \equiv B_x / \sqrt{\mu_0 \rho}$, and $\rho \equiv \sum_{\alpha} m_{\alpha} n_{\alpha}$, summing Equation 18 with mass weights gives

$$\frac{U_x}{V_{A,x}} \Big|_{\pm} = \frac{\sqrt{\mu_0} \sum_{\alpha} m_{\alpha} \Gamma_{\alpha}}{B_z \sqrt{\rho|_{\pm}}}. \quad (19)$$

For matched asymptotic density, $\rho(+\infty) = \rho(-\infty) \equiv \rho_{\infty}$, both ΔU_x and $\Delta V_{A,x}$ are proportional to ΔB_x , and

$$\frac{\Delta U_x}{\Delta V_{A,x}} = \frac{\sqrt{\mu_0} \sum_{\alpha} m_{\alpha} \Gamma_{\alpha}}{B_z \sqrt{\rho_{\infty}}}. \quad (20)$$

The apparent B_z dependence can be eliminated using transverse stress balance. Combining Equation 12–Equation 13 across species with Ampere’s law yields

$$\begin{aligned} \sum_{\alpha} m_{\alpha} \Gamma_{\alpha} u_{\alpha x} + \Pi_{xz} &= \frac{B_x B_z}{\mu_0} + C_x \\ \sum_{\alpha} m_{\alpha} \Gamma_{\alpha} u_{\alpha y} + \Pi_{yz} &= \frac{B_y B_z}{\mu_0} + C_y, \end{aligned} \quad (21)$$

where $\Pi_{iz} \equiv \sum_{\alpha} P_{iz,\alpha}$ and C_x , C_y are integration constants. Evaluating Equation 21 asymptotically and substituting Equation 18 gives

$$\mu_0 \sum_{\alpha} \frac{m_{\alpha} \Gamma_{\alpha}^2}{n_{\alpha}|_{\pm}} = B_z^2 (1 - \Lambda_d|_{\pm}), \quad \Lambda_d|_{\pm} \equiv \frac{\mu_0 (\Pi_{xz}|_{\pm} - C_x)}{B_x|_{\pm} B_z}. \quad (22)$$

The dimensionless coefficient Λ_d is a dynamical stress factor built from the asymptotic states. Solving Equation 22 for B_z and substituting into Equation 20 yields

$$\left| \frac{\Delta U_x}{\Delta V_{A,x}} \right| = \frac{\sum_{\alpha} m_{\alpha} \Gamma_{\alpha}}{\sqrt{\rho_{\infty} \sum_{\alpha} m_{\alpha} \Gamma_{\alpha}^2 / n_{\alpha}|_{\pm}}} \sqrt{1 - \Lambda_d|_{\pm}}. \quad (23)$$

The first factor encodes multifluid structure and is bounded by unity by the Cauchy–Schwarz inequality. The second factor captures anisotropy and agyrotropy contributions.

For gyrotropic pressure, $\mathbf{P}_\alpha = p_{\perp,\alpha} \mathbf{I} + (p_{\parallel,\alpha} - p_{\perp,\alpha}) \hat{\mathbf{b}} \hat{\mathbf{b}}$, with $\Lambda_\alpha \equiv \mu_0 (p_{\parallel,\alpha} - p_{\perp,\alpha}) / B^2$, the off-diagonal stress is $\Pi_{xz} = (B_x B_z / \mu_0) \sum_\alpha \Lambda_\alpha$. Thus $\Lambda_d = \sum_\alpha \Lambda_\alpha$ when $C_x = 0$.

When the stress factor is symmetric across the sheet, $\Lambda_d|_+ = \Lambda_d|_- \equiv \Lambda_d$, the modified Alfvén velocity $V'_{A,x} \equiv V_{A,x} \sqrt{1 - \Lambda_d}$ satisfies $\Delta V'_{A,x} = \sqrt{1 - \Lambda_d} \Delta V_{A,x}$. The ratio of ΔU_x to $\Delta V'_{A,x}$ then depends only on the multifluid factor. In the single-fluid limit this reduces to $\Delta U_x = \pm \Delta V'_{A,x}$. For two ion fluids with equal mass and equal but opposite normal velocities, $m_1 = m_2$ and $u_{z,1}(\pm\infty) = -u_{z,2}(\pm\infty)$, Equation 23 becomes

$$\left| \frac{\Delta U_x}{\Delta V'_{A,x}} \right| = \left| \frac{n_1(\pm\infty) - n_2(\pm\infty)}{n_1(\pm\infty) + n_2(\pm\infty)} \right|. \quad (24)$$

A.2 Results

We now apply the model to rotational current sheets. Assume gyrotropic pressure for each species. Let $\theta(z)$ denote the azimuthal angle of $\mathbf{B}_{xy} \equiv (B_x, B_y)$, so that $B_x = B_T \cos \theta$, $B_y = B_T \sin \theta$, and $B_T = |\mathbf{B}_{xy}|$. The transverse rotation is partial when $\theta_+ - \theta_- \neq k\pi$ for any integer k .

Under the gyrotropic assumption, the integration constants in Equation 21 vanish for any partial rotation. Decompose each transverse velocity along $\hat{\mathbf{b}}_T = (\cos \theta, \sin \theta)$ and $\hat{\mathbf{b}}_\perp = (-\sin \theta, \cos \theta)$,

$$u_{\alpha T} \equiv u_{\alpha x} \cos \theta + u_{\alpha y} \sin \theta, \quad u_{\alpha \perp} \equiv -u_{\alpha x} \sin \theta + u_{\alpha y} \cos \theta.$$

Projecting Equation 21 onto $\hat{\mathbf{b}}_\perp$ eliminates magnetic and gyrotropic pressure-anisotropy terms, leaving

$$\sum_\alpha m_\alpha \Gamma_\alpha u_{\alpha \perp} = -C_x \sin \theta + C_y \cos \theta.$$

Asymptotically, Equation 18 and its y counterpart imply $u_{\alpha \perp}|_\pm = 0$. For partial rotations, the two asymptotic equations form a nonsingular homogeneous system for (C_x, C_y) , so

$C_x = C_y = 0$. The singular π reversal also gives $C_x = C_y = 0$ when the asymptotic state is symmetric in density and dynamical stress factor. Therefore,

$$\sum_{\alpha} m_{\alpha} \Gamma_{\alpha} u_{\alpha\perp} = 0. \quad (25)$$

A second constraint follows from Ampere's law:

$$\sum_{\alpha} q_{\alpha} n_{\alpha} B_T u_{\alpha\perp} = \frac{1}{2\mu_0} \frac{dB_T^2}{dz}.$$

We now specialize to current sheets with constant total magnetic-field magnitude $|\mathbf{B}| = \text{const}$, a common condition in the solar wind (Gosling et al., 2009; Tsurutani et al., 1994), and to two counter-streaming proton populations plus one isotropic massless electron population. Since B_z is constant, $B_T = B_0$ is constant and $\mathbf{B}_{xy}$ merely rotates. The Ampere-sum relation gives $\sum_{\alpha=1}^2 n_{\alpha} u_{\alpha\perp} = 0$. With Equation 25, the two-ion system forces $u_{\alpha\perp} = 0$ for distinct normal flow velocities, so each ion transverse velocity lies along $\mathbf{B}_{xy}$:

$$u_{\alpha y} B_x - u_{\alpha x} B_y = 0. \quad (26)$$

Projecting transverse momentum along $\mathbf{B}_{xy}$ yields

$$K_{\alpha} \equiv m_{\alpha} \Gamma_{\alpha} u_{\alpha T} + \frac{\Lambda_{\alpha} B_0 B_z}{\mu_0} = \text{const} . \quad (27)$$

Projecting perpendicular to $\mathbf{B}_{xy}$ gives

$$K_{\alpha} \theta' = e(\Gamma_{\alpha} B_0 - n_{\alpha} u_{\alpha} B_z), \quad (28)$$

where $' = d/dz$. Ampere's law reduces to

$$\theta' = \mu_0 e \left(\frac{\Gamma_e}{B_z} - \frac{\sum_{\alpha=1}^2 n_{\alpha} u_{\alpha}}{B_0} \right). \quad (29)$$

In the asymptotic region, $\theta' = 0$, and Equation 28 enforces $n_{\alpha} u_{\alpha}|_{\infty} = \Gamma_{\alpha} B_0 / B_z$. Thus

$$K_{\alpha} \theta' = e B_z (n_{\alpha} u_{\alpha}|_{\infty} - n_{\alpha} u_{\alpha}). \quad (30)$$

Under gyrotropy, $P_{zz,\alpha} = p_{\perp,\alpha} + \Lambda_\alpha B_z^2/\mu_0$, so Equation 14 becomes

$$\frac{d}{dz} \left(\frac{m_\alpha \Gamma_\alpha^2}{n_\alpha} + p_{\perp,\alpha} + \frac{\Lambda_\alpha B_z^2}{\mu_0} \right) = -en_\alpha \frac{d\varphi}{dz}. \quad (31)$$

The variables n_α , $p_{\perp,\alpha}$, and Λ_α are decoupled from θ . A simple closure $p_{\perp,\alpha} = p_{\perp,\alpha}(n_\alpha, B)$ and $\Lambda_\alpha = \Lambda_\alpha(n_\alpha, B)$ for every species, combined with a relation between φ and n_e and constant $|\mathbf{B}|$, would over-determine the system and admit only the trivial uniform solution. We therefore leave pressure as a free parameter; equivalently, Equation 31 lets one ion density profile be specified freely, with remaining densities, pressures, and φ determined self-consistently.

For concrete profiles we take isotropic pressure, $\Lambda_\alpha = 0$, set $\theta(0) = \pi/2$, and choose a Lorentzian profile for the first ion population:

$$n_1(z) = n_1(\infty) + \frac{\kappa \Gamma_1}{V_A} \frac{1}{1 + (z/L)^2},$$

where L is the current-sheet scale, $V_A \equiv B_z/\sqrt{\mu_0 m_p n(\infty)}$ is the asymptotic Alfvén speed in the z direction, and κ controls the density perturbation. Other localized profiles give the same asymptotic Alfvénicity and qualitatively similar structure. Solving Equation 30 gives

$$\theta(z) = \frac{\pi}{2} - \frac{e\kappa L B_z \tan^{-1}(z/L)}{m_p V_A},$$

with $eLB_z/m_p V_A = L/d_i$. The ion densities are

$$n_{\alpha(z)} = n_{\alpha(\infty)} + \frac{\hat{n}_\alpha}{1 + (z/L)^2}$$

$$n(z) \equiv n_1(z) + n_2(z) = n(\infty) + \frac{\hat{n}}{1 + (z/L)^2},$$

where $\hat{n}_\alpha \equiv n_{\alpha(0)} - n_{\alpha(\infty)} = \kappa \Gamma_\alpha/V_A$ and $\hat{n} \equiv n(0) - n(\infty) = \kappa \sum_{\alpha=1}^2 \Gamma_\alpha/V_A$.

The transverse current and ion bulk-flow profiles are

$$\begin{aligned}
J_{j(z)} &= \frac{e\kappa B_z}{\mu_0 m_p V_A} \frac{B_{j(z)}}{1 + (z/L)^2}, \quad J_z = 0, \\
J_{e,j}(z) &= -\frac{eB_{j(z)}}{B_z} \sum_{\alpha=1}^2 \Gamma_\alpha, \quad J_{e,z} = -e \sum_{\alpha=1}^2 \Gamma_\alpha, \\
J_{i,j}(z) &= J_{j(z)} - J_{e,j}(z), \quad J_{i,z} = e \sum_{\alpha=1}^2 \Gamma_\alpha, \\
U_{j(z)} &= \frac{J_{i,j}(z)}{en(z)}, \quad U_{z(z)} = \frac{1}{n(z)} \sum_{\alpha=1}^2 \Gamma_\alpha,
\end{aligned}$$

for $j \in \{x, y\}$. Using $\hat{n}_\alpha/\hat{n} = \Gamma_\alpha/\sum_{\alpha=1}^2 \Gamma_\alpha$, the parameters can be written in terms of densities:

$$\begin{aligned}
\kappa &= \sqrt{\sum_{\alpha=1}^2 \frac{\hat{n}_\alpha^2}{n(\infty)n_{\alpha(\infty)}}} \\
\sum_{\alpha=1}^2 \Gamma_\alpha &= \sqrt{\frac{B_z^2}{\mu_0 m_p} \frac{\hat{n}^2}{\sum_{\alpha=1}^2 \hat{n}_\alpha^2/n_{\alpha(\infty)}}} = \frac{V_A \hat{n}}{\kappa}.
\end{aligned} \tag{32}$$

In dimensionless variables, normalized by B_z , $n(\infty)$, d_i , and V_A , the profiles become

$$\begin{aligned}
\theta(z) &= \frac{\pi}{2} - \frac{\kappa L \tan^{-1}(z/L)}{d_i} \\
\frac{\mathbf{J}}{eV_A n(\infty)} &= \frac{\mathbf{B}(z)}{B_z} \frac{\kappa}{1 + (z/L)^2} \\
\frac{\mathbf{J}_e}{eV_A n(\infty)} &= -\frac{\mathbf{B}(z)}{B_z} \frac{\hat{n}}{\kappa n(\infty)} \\
\frac{\mathbf{U}}{V_A} &= \frac{\mathbf{B}(z)}{B_z} \frac{n(\infty)}{n(z)} \left(\frac{\kappa}{1 + (z/L)^2} + \frac{\hat{n}}{\kappa n(\infty)} \right).
\end{aligned}$$

Here $\mathbf{B}$, $\mathbf{J}$, $\mathbf{J}_e$, and $\mathbf{U}$ denote transverse components; the z components are given above.

The system is fully determined by κ , $\sum_{\alpha} \Gamma_\alpha$, L , and B_0 , or equivalently by $\hat{n}_\alpha$, $n_{\alpha(\infty)}$, L , and B_0 . For the symmetric case $n_1(\infty) = n_2(\infty)$ and $u_{1z}(\infty) = -u_{2z}(\infty)$, with $L = d_i$, $\kappa = 1$, and $B_0 = 2B_z$, Figure A.2 shows the field, density, velocity, and current profiles. Since

$\sum_{\alpha} \Gamma_{\alpha} = 0$ and $\hat{n} = 0$, the electron current vanishes and B_y has no asymptotic background, corresponding to a 180° magnetic-field rotation.

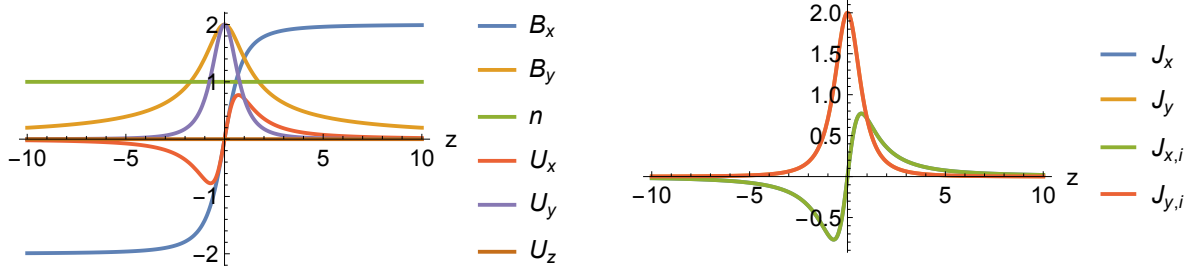


Figure A.2: Left: Magnetic field, ion density, and ion bulk velocity for $n_1 = n_2$, $u_1 = -u_2$, $L = d_i$, $\sum_{\alpha=1}^2 \Gamma_{\alpha} = \hat{n}V_A = 0$, and $B_0 = 2B_z$. Right: Current density profiles for the same case. The blue line (J_x) coincides with the green line ($J_{x,i}$), and the yellow line (J_y) coincides with the red line ($J_{y,i}$).

Figure A.2 shows constant density and zero U_z because $\sum_{\alpha} \Gamma_{\alpha} = 0$. The bulk flow has U_y peaked at the sheet center and U_x reversing across the center. The velocity magnitude vanishes far from the sheet, so the velocity jump is zero. This symmetric case is the limiting configuration where stress balance across a current sheet with $B_z \neq 0$ is maintained entirely by counter-streaming ion beams rather than by a net bulk velocity jump. Substitution into Equation 24 confirms that the stress balance is satisfied.

For asymmetric beams we set $B_{y(\infty)} = B_0/2$, $B_0 = 2B_z$, and use two ion populations with opposite normal velocities but different densities. Varying $n_1(\infty)$ leaves the magnetic-field profiles nearly unchanged, while density and velocity profiles vary strongly.

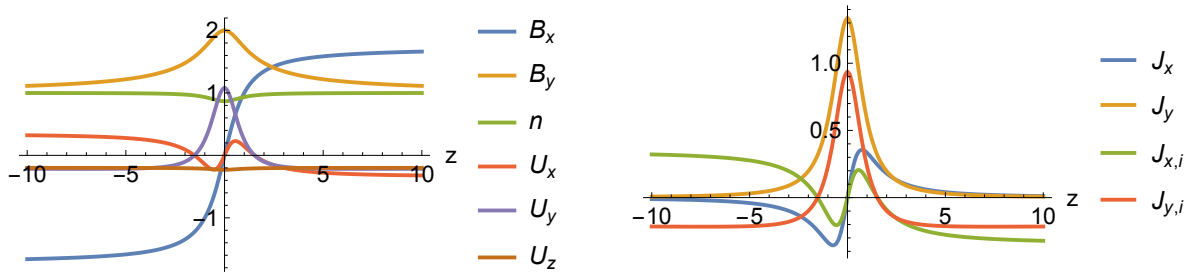


Figure A.3: Same as Figure A.2, but for two ion populations with $n_1(\infty)/n_2(\infty) = 1.5$ and $B_{y(\infty)} = B_0/2 = B_z$.

Figure A.3 shows results for $n_1(\infty)/n_2(\infty) = 1.5$. The reversal component B_x resembles the symmetric case, whereas the B_y peak is embedded in a constant background. The

density and U_z profiles show a small minimum at the sheet center; pressure balance then requires a compensating temperature maximum. Unlike the symmetric case, the ion velocities remain finite at the sheet boundaries and have a bulk velocity jump $\Delta U_x = |(n_1(\infty) - n_2(\infty))/(n_1(\infty) + n_2(\infty))|\Delta V_{A,x}$. Finite $\hat{n}$ also produces nonzero electron currents. Ion and electron currents compensate outside the sheet, leaving nonzero total current only inside.

To illustrate density control of velocity structure, Figure A.4 shows normalized U_x/V_A and U_y/V_A for different $n_1(\infty)$. The symmetric case $n_1(\infty) = 0.5$ has zero velocity jump. As $n_1(\infty)$ decreases toward zero, the jump increases. Thus the model regulates ΔU_x through ion-beam density contrast. There is no U_y jump across the sheet, but asymptotic $U_{y(\infty)}$ depends on $n_1(\infty)$ and vanishes in the symmetric case.

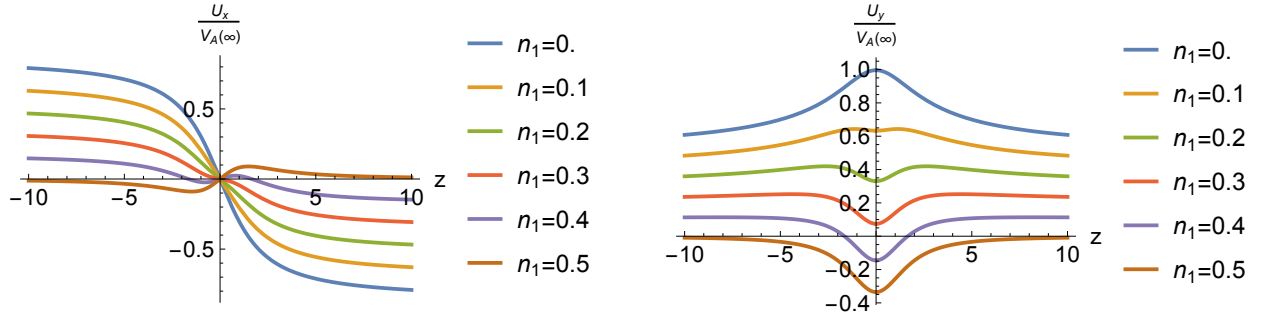


Figure A.4: Plasma velocity U_x (left) and U_y (right) normalized by asymptotic Alfvén velocity $V_{A(\infty)} = B_0/\sqrt{\mu_0 m_p n(\infty)}$ for different $n_1(\infty)$.

The spatial profiles of U_x and U_y follow B_x and B_y . Therefore $U_x/V_{A,x}$ and $U_y/V_{A,y}$ quantify how much Alfvén-velocity variation is reflected in plasma flow. Figure A.5 shows that the normalized profiles are identical for the two components and depend only on $n_1(\infty)$. As $n_1(\infty)$ approaches zero, the boundary value tends to unity, $U_x/V_{A,x} \rightarrow 1$, recovering the single-fluid rotational-discontinuity limit.

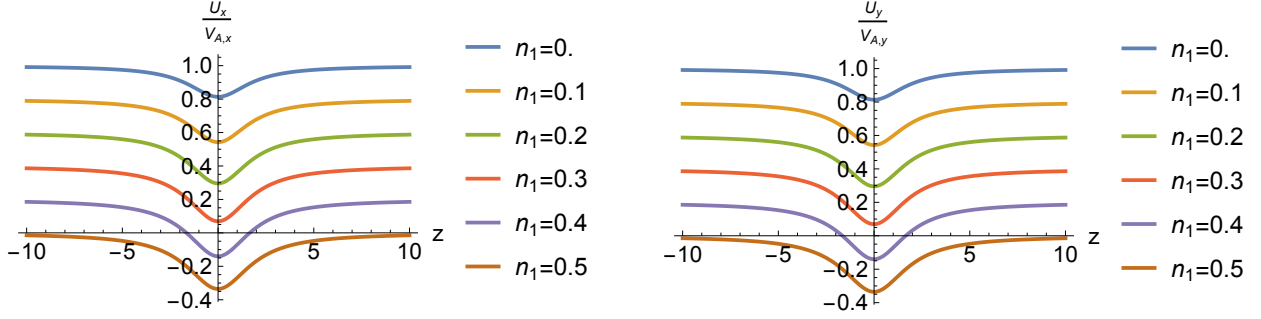


Figure A.5: Plasma velocity U_x (left) and U_y (right) normalized by local Alfvén velocities $V_{A,x}(z) = B_{x(z)}/\sqrt{\mu_0 m_p n(z)}$ and $V_{A,y}(z) = B_{y(z)}/\sqrt{\mu_0 m_p n(z)}$ for different $n_1(\infty)$.

A.3 Discussion

This work presents a phenomenological multifluid equilibrium model of current sheets with arbitrary Alfvénicity. The model naturally accommodates interpenetrating ion beams and a tunable velocity structure controlled by relative ion-population densities. Its primary applications are current sheets in the solar wind (Artemyev et al., 2019a) and planetary magnetotails (Kamaletdinov et al., 2024).

Two kinetic effects remain beyond this fluid treatment. First, trapped ions that oscillate within the current-sheet potential well contribute locally to current and pressure, modifying the internal profile without changing the asymptotic stress balance set by freely streaming populations. Second, the boundary between ion populations in velocity space, sharp in the uniform-field asymptotic region, becomes diffuse within the sheet: nonadiabatic scattering drives slow diffusion of transient Speiser-like ions into quasi-trapped orbits (Mingalev et al., 2012; Zelenyi et al., 2002; 2003), progressively reducing the effective ion density contrast and reshaping the current profile. The equilibria derived here should therefore be understood as quasi-stationary snapshots along this slow evolution, satisfying Equation 23 at each instant.

The model is not a unique equilibrium solution. Three considerations nevertheless make this subclass physically relevant. First, the constant- $|\mathbf{B}|$ condition used above is a known nonlinear attractor of Alfvénic relaxation in simulations (Matteini et al., 2024; Tenerani & Velli, 2018). Second, the two-fluid tearing-mode analysis of (Shi et al., 2021) identifies the

most stable configuration as one with finite normal B_z and counter-streaming ion flows, both embedded here. Third, counter-streaming ion populations are generic in current-sheet environments, arising from distinct solar origins, reflected and pickup ions in the solar wind, and opposite hemispheric sources in planetary magnetospheres. Further work on kinetic properties and dynamical selection (Yoon et al., 2023; 2024) is still needed.

Within the model, $\Delta U_x / \Delta V_{A,x}$ is controlled by density asymmetry between ion populations (Equation 24). Configurations with $n_1 \gg n_2$ approach the single-fluid limit, while balanced densities give lower ratios. Solar-wind observations typically show sub-unity ratios (Artemyev et al., 2019b; De Keyser et al., 1998), consistent with multiple ion populations of comparable density and the effective pressure anisotropy supported by counter-streaming beams (Abraham-Shrauner, 1967; Hudson, 1970). Internal structure is also likely shaped by effects beyond the gyrotropic specialization used here, especially pressure nongyrotropy associated with nonadiabatic ion motion across thin sheets (Artemyev et al., 2020b). Incorporating nongyrotropic stresses into this multifluid framework is a natural next step.

A.4 Data Availability

The codes and data supporting this study are available at https://github.com/Beforerr/cs_theory.

A.5 Appendix

This appendix describes the procedures used to identify current sheets and characterize their properties for Figure A.1.

We use three data sets collected by PSP, ARTEMIS, and Wind. Magnetic-field measurements for PSP were obtained with the FIELDS instrument suite (Bale et al., 2016), while plasma velocity and density were provided by the SPAN-Ion electrostatic analyzer on SWEAP (Kasper et al., 2016). For ARTEMIS, magnetic-field data were acquired with the Fluxgate Magnetometer (Auster et al., 2008), and plasma measurements were obtained from the Electrostatic Analyzers (McFadden et al., 2009). Wind used the Magnetic Field

Investigation instrument (Lepping et al., 1995) for magnetic-field measurements and 3D Plasma Analyzer electrostatic analyzers on the Solar Wind Experiment (Ogilvie et al., 1995) for proton velocity and density.

To identify current sheets, we use the sliding three-interval method of (Liu et al., 2022b). Around each sample time t , a window of lag T is divided into pre-, middle-, and post-intervals with magnetic-field segments $\mathbf{B}_-$, $\mathbf{B}_0$, and $\mathbf{B}_+$. A candidate is flagged when (1) $\sigma(\mathbf{B}_0) > 2 \max[\sigma(\mathbf{B}_-), \sigma(\mathbf{B}_+)]$ and (2) $\sigma(\mathbf{B}_- + \mathbf{B}_+) > \sigma(\mathbf{B}_-) + \sigma(\mathbf{B}_+)$, where σ denotes standard deviation. After identifying candidates, we apply maximum variance analysis (Sonnerup & Scheible, 1998) to transform magnetic field and plasma velocity into the local current-sheet coordinate system **lmn**.

Appendix B

The JuliaSpacePhysics Ecosystem: High-Performance, Modular, and Scalable Software for Space Physics Data Analysis

B.1 Introduction

The continued expansion of space physics missions—particularly multi-spacecraft constellations with increasingly high-cadence measurements—presents growing challenges for data discovery, access, processing, and analysis. Modern missions routinely generate large, heterogeneous datasets whose volume and complexity place substantial demands on existing analysis workflows, making scalable, efficient, and sustainable software frameworks essential for the community.

Historically, space physics data analysis has relied on programming environments such as IDL, MATLAB, and, more recently, Python. While these tools have enabled significant scientific advances, each exhibits notable limitations. IDL is proprietary, restricting free distribution and long-term sustainability, and suffers from a single-namespace design that leads to conflicts when combining multiple libraries. MATLAB faces similar licensing constraints—a practical barrier for scaling to clusters, continuous integration, containers, or broad distribution—and encounters performance bottlenecks when moving beyond built-in vectorized operations to custom loops, complex data structures, or user-defined logic. Python has become the dominant open-source language in heliophysics due to its extensive ecosystem and accessibility, but its interpreted execution model imposes performance limitations for computationally intensive tasks; achieving high performance typically requires pushing work into vectorized libraries, JIT frameworks, or compiled-language extensions.

This chapter presents the **JuliaSpacePhysics ecosystem**, a modular and interoperable software framework for space physics data analysis built on the Julia programming

language. This ecosystem underpins the large-scale multi-mission current sheet surveys (Chapter 2 and Chapter 3) and the test-particle transport simulations (Chapter 4 and Chapter 5) developed in this thesis. Julia combines high-level expressiveness with near-compiled-language performance through just-in-time compilation, multiple dispatch, and strong support for abstract interfaces, enabling both rapid development and efficient execution within a single language. Rather than replacing existing community tools, JuliaSpacePhysics is designed to complement them: the ecosystem provides native, high-performance implementations for core analysis tasks alongside thin wrappers around established Python and Fortran libraries to maximize code reuse.

A defining feature of the ecosystem is its abstraction-driven design. Analysis routines are defined against abstract interfaces for time series and multi-dimensional data, decoupling scientific computation from file format, metadata standard, mission, and memory layout. A mapping-based metadata strategy ensures interoperability across ISTP, SPASE, and related conventions. This approach, combined with optimized I/O layers supporting lazy loading, memory mapping, and parallel processing, yields performance improvements of one to three orders of magnitude relative to common scripting-language implementations for tasks including moment calculations, coordinate transformations, wave analysis, dispersion solvers, and multi-spacecraft methods. These gains enable not only faster processing but qualitatively new workflows—interactive recomputation during visualization, large parameter sweeps, and ensemble-scale statistical studies—that are impractical in traditional scripting environments.

The ecosystem’s decentralized architecture distributes functionality across interoperable packages built upon stable base APIs, promoting community-driven development, reducing maintenance burden, and providing a scalable foundation for future missions and analysis techniques. The remainder of this chapter introduces the core design principles, surveys the key packages, and demonstrates how this framework addresses both current and anticipated data-analysis challenges in space physics research.

B.2 Data Discovery, Access, and Loading

Historically, space physics mission data were often distributed directly by individual instrument teams or host institutions. While this model enabled early access and mission-specific expertise, it also posed challenges for data discovery, cross-mission/cross-instrument analysis, and long-term usability. Over time, a broad community consensus emerged recognizing the value of centralized data repositories or virtual observatories, which significantly lower barriers for users seeking to locate, access, and combine observations from multiple missions (Erard et al., 2018; Génot et al., 2021).

These efforts have led to the establishment of several major space physics data archives. Notable examples in the United States include NASA Coordinated Data Analysis Web (CDAWeb) (NASA CDAWeb Development Team, 2019), which provides a comprehensive repository for non-solar heliophysics data, the MADRIGAL Database, which serves upper atmospheric science observations from a wide range of ground-based and space-borne instruments, and virtual solar observatory (VSO) (Hill et al., 2009), which provides access to data and images from the major sources of solar data. In Europe, comparable initiatives such as Automated Multi-Dataset Analysis (AMDA) have centralized multi-mission datasets and provided advanced tools for data analysis and visualization (Génot et al., 2021). Together, these archives form the backbone of modern space physics data access (Burrell et al., 2018).

Within the JuliaSpacePhysics ecosystem, these existing data infrastructures are leveraged to provide data access. Dedicated Julia client packages are developed to interface directly with established repositories, providing unified programmatic access to metadata queries, data discovery, and file retrieval across missions and instruments. For example, CDAWeb.jl provides a native Julia interface to NASA CDAWeb using their RESTful Web Service API, enabling users to query available datasets, inspect metadata, and download mission data products in a reproducible and scriptable manner. Similarly, Madrigal.jl supports access to the Madrigal Database, facilitating retrieval of ionospheric and thermospheric measurements and associated experiment metadata. Beyond Julia-native clients, the ecosystem emphasizes wrapping and reusing mature external libraries to maximize interoperability and avoid redundant development. For solar and heliospheric data access, Julia wrappers around the Python-based SunPy ecosystem enable interaction with solar virtual observatories and related services. This approach allows users to rely on well-established

community tools for data discovery and retrieval, while performing subsequent analysis and computation within Julia. Likewise, `Speasy.jl` provides access to the AMDA database and other supported services by wrapping the underlying `Speasy` library and exposing its functionality through idiomatic Julia interfaces. Complementing archive-specific interfaces, the ecosystem also supports the Heliophysics Application Programming Interface (HAPI), a modern, standardized protocol for dataset discovery and access. HAPI enables browsing of distributed data catalogs, retrieval of parameter metadata, and streaming of time series data from heterogeneous web services, independent of the underlying archive implementation. Table B.2 summarizes the data access interfaces supported by the ecosystem.

Table B.2: Data Access Interfaces in the JuliaSpacePhysics Ecosystem. All retrieved data files are cached locally to support efficient reuse and reproducible workflows.

Data source / service	Scope	Julia package	Data delivery
NASA CDAWeb	Heliospheric & magnetospheric missions	<code>CDAWeb.jl</code>	CDF files (RESTful web services)
Madrigal Database	Ionosphere & thermosphere	<code>Madrigal.jl</code>	Experiment-specific formats
AMDA	Multi-mission plasma data	<code>Speasy.jl</code>	CDF / derived products
Heliophysics Application Programming Interface	Distributed time series	<code>HAPIClient.jl</code>	Streamed arrays
SunPy	Solar observatories & VO services	<code>SunPy.jl</code>	FITS / mission formats

A central technical foundation of many space physics archives is the Common Data Format (CDF), which remains one of the most widely used formats for in situ observations. Recognizing its importance, the JuliaSpacePhysics ecosystem includes a modern, high-performance CDF reader that exploits multi-threading and lazy access to both data and metadata. While several CDF readers already exist—notably NASA’s reference C implementation and the Python package `cdflib`—these widely used tools do not support multi-threaded access and can become performance bottlenecks for large datasets. More

recent efforts, such as CDFpp, demonstrate that substantial performance gains are possible with modern design choices. Rather than eagerly loading all variables contained in a CDF file, the Julia CDF implementation accesses only those variables explicitly requested by the user like CDFpp. This design is particularly advantageous for complex datasets containing dozens or hundreds of variables, many of which are irrelevant to a given analysis. Building on this idea, lazy loading is extended beyond the variable level to the temporal dimension. When an analysis targets a restricted time interval, only the subset of samples within that interval is retrieved from disk, rather than loading the full time series. This fine-grained data access strategy substantially reduces I/O overhead and memory usage, leading to significant acceleration in analysis workflows.

Together, these archive-aware clients, standardized streaming interfaces, and high-performance I/O capabilities enable efficient and scalable interaction with distributed space physics data repositories. Moreover, by combining Julia-native packages with thin wrappers around established external libraries, the JuliaSpacePhysics ecosystem remains closely aligned with evolving community standards while fully leveraging Julia’s performance and abstraction capabilities. Collectively, these design choices provide a robust foundation for multi-mission integration, upon which the higher-level analysis and visualization capabilities of the JuliaSpacePhysics ecosystem are built.

B.3 Data and Metadata Model

B.3.1 Abstract Interfaces for Heterogeneous Data Formats and Representations

Space physics datasets are not only geographically and administratively distributed, but also stored in a wide range of file formats. While the Common Data Format (CDF) remains dominant for in situ time series data, many missions distribute products in additional formats. Upper-atmosphere observations are frequently provided in NetCDF (Rew & Davis, 1990), solar imaging data commonly use FITS (Pence et al., 2010), and derived or summary products often appear in plain-text formats such as CSV. Each format

reflects specific scientific and operational requirements and carries its own conventions for metadata, dimensionality, and data organization. Supporting integrative, multi-mission science across this diversity remains a fundamental technical challenge.

Existing software frameworks typically address format heterogeneity by loading disparate data products into framework-specific internal data structures. SPEDAS maps data into *tplot* variables, spacepy uses *datamodel* objects, and pysat employs *instrument* containers (Angelopoulos et al., 2019; Cai et al., 2022; Grimes et al., 2022; Niehof et al., 2022; Stoneback et al., 2018; 2023). Each encapsulates both data and metadata in a file-format agnostic manner, providing consistent user interfaces and standardized access patterns. However, this approach tightly couples file format, in-memory representation, and analysis routines, making it difficult to extend to new storage backends or computational environments without substantial adaptation.

Beyond file-format heterogeneity, modern workflows introduce a second layer of diversity: runtime data representations. Data may reside in conventional CPU memory, on accelerators such as GPUs, or in distributed or memory-mapped arrays for large-scale analysis. These distinctions are largely orthogonal to file format, yet they strongly influence performance, scalability, and the feasibility of advanced workflows. Ecosystems built around fixed array abstractions (e.g., NumPy or xarray) often require refactoring or format-specific code paths to accommodate such variation.

The JuliaSpacePhysics ecosystem adopts a fundamentally different strategy. Rather than coercing all data into a single internal container, it defines analysis routines in terms of abstract interfaces for multi-dimensional time series. These interfaces preserve the semantic and structural characteristics of native data formats while exposing a common set of operations. Beyond Julia’s standard array interface (`axes`, `ndims`, `size`, `similar`), domain-specific accessors are provided: `tdimnum(x)` and `times(x)` retrieve the time dimension and timestamps, while `dim(x, i)` or `dim(x, name)` access dimension-specific coordinate information.

By programming against this interface rather than concrete types, the same analysis code operates uniformly on data from different file formats and memory spaces. Julia’s native support for abstract array types and multiple dispatch enables scientific routines to be

decoupled from both file format and memory layout. This abstraction-first design yields several advantages. First, it eliminates the need to normalize datasets into a framework-specific representation, reducing conversion overhead and preserving structural flexibility. Second, it allows routines to operate transparently on CPU arrays, GPU arrays, or other specialized storage backends without modification. Third, it promotes extensibility: functions written against the abstract interface automatically generalize to new formats and storage mechanisms as they are introduced. Together, these properties provide a scalable foundation for integrative space physics research as datasets grow in size, complexity, and computational demand.

B.3.2 Metadata Interoperability and Mapping Across Standards

Metadata are essential for the correct interpretation, visualization, and transformation of scientific measurements. Over time, multiple metadata conventions have emerged to serve different communities and infrastructures. Prominent examples include the International Solar Terrestrial Physics (ISTP) metadata conventions embedded in CDF files (Lewis et al., 2023), which underpin a large fraction of heliospheric and magnetospheric mission products. More recently, community initiatives such as the SPASE Data Model have sought to standardize data discovery and access across archives (Roberts et al., 2018).

Rather than collapsing these heterogeneous standards into a single unified schema, the JuliaSpacePhysics ecosystem adopts a mapping-based approach. Metadata originating from different sources are interpreted and translated into a small set of semantically meaningful abstract attributes consumed by analysis, visualization, and coordinate-transformation routines. Similar mapping strategies have been employed by other systems—for example, the AMDA team maps EPNcore (Europlanet core metadata) data model and SPASE dictionary elements within their internal database (Génot et al., 2021).

This approach preserves the richness and intent of existing metadata standards while avoiding the rigidity and maintenance burden associated with enforcing a single global schema. In practice, high-level functions—such as plotting, unit handling, and coordinate transformations—operate consistently across datasets obtained from disparate archives. As illustrated in Figure B.1, identical visualization and transformation routines can be applied

to time series retrieved from a HAPI-enabled server and from a local CDF file. Despite differences in underlying metadata formats and storage representations, physical context such as units, coordinate systems, and time bases is interpreted correctly in each case.

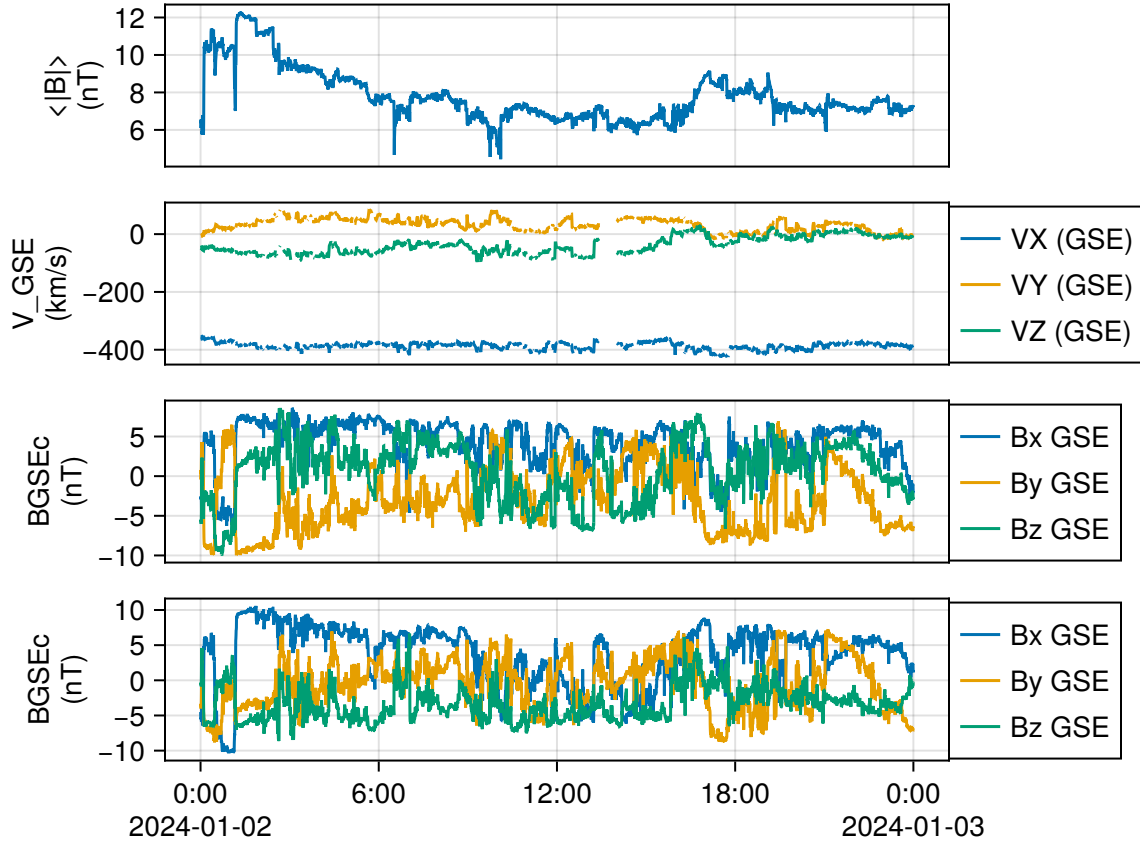


Figure B.1: Time series plots from different data sources

By focusing on metadata mapping rather than schema unification, the JuliaSpacePhysics ecosystem decouples scientific analysis from both data format and metadata standard. This design enhances flexibility, robustness, and forward compatibility as new archives, protocols, and metadata conventions continue to emerge.

B.4 Accelerated Computation and Interactive Exploration

A key advantage of adopting Julia is the substantial acceleration of computational workflows, coupled with strong support for interactive scientific exploration. Julia code is

just-in-time compiled via LLVM (Bezanson et al., 2017), enabling performance comparable to statically compiled languages such as C and Fortran for many numerical workloads. At the same time, Julia preserves a high-level, expressive syntax that is well suited to mathematical and physical modeling and offers a highly developed read-eval-print loop (REPL) environment. This combination enables rapid prototyping, exploratory data analysis, and iterative refinement—capabilities that are essential when working with complex, multi-instrument space physics datasets.

These language-level advantages do not require that an entire space physics workflow be reimplemented in Julia from the outset. In a mature scientific domain, effective acceleration is more naturally achieved by first integrating with existing, well-established software ecosystems. Julia’s interoperability with Python, Fortran, and C (Rowley, 2022) enables a development strategy in which trusted community tools are reused for data discovery and legacy functionality, while performance-critical analysis and interactive exploration are incrementally migrated to Julia. In this sense, interoperability serves as the first stage of acceleration: it lowers the barrier to entry, preserves continuity with existing workflows while revealing the specific computational bottlenecks that motivate targeted Julia-native development.

B.4.1 Leveraging Existing Ecosystems Through Interoperability

Building on this strategy, a core design principle of the JuliaSpacePhysics ecosystem is to extend, rather than replace, the extensive software infrastructure within the space physics community. By directly calling mature, well-tested libraries from other languages, the ecosystem preserves decades of domain expertise while selectively introducing Julia-native abstractions and implementations where improved performance, flexibility, or extensibility are required.

The development of this interoperability layer initially focused on enabling access to existing analysis workflows provided by the Python-based SPEDAS framework (Grimes et al., 2022). Early implementations emphasized lightweight wrappers that allowed Julia users to invoke SPEDAS functionality directly. As these hybrid workflows were applied in active research, however, performance bottlenecks and architectural constraints became apparent

—particularly for large-scale, iterative analyses. (For example, although PySPEDAS heavily depends on the numpy arrays or xarray objects, the interface it exposed to users is a string where corresponding data is stored in global objects). These limitations, together with evolving requirements for extensibility, motivated a gradual expansion beyond a pure wrapper model. Over time, Julia-native components were introduced to complement existing tools, leading to a system that selectively diverges from, rather than mirrors, its Python counterparts.

Within the ecosystem, several packages provide thin, idiomatic Julia interfaces to widely used external libraries. For Python-based tools, packages such as `Speasy.jl` and `SunPy.jl` expose core functionality directly to Julia users, enabling access to established virtual observatories and data services. In these workflows, Python is typically used for data discovery and retrieval, while the resulting data arrays are transferred into Julia for subsequent processing. Utilizing the fast non-copying conversion of numeric arrays from Python to Julia in `PythonCall.jl`, the overhead of data transfer is negligible. This approach avoids unnecessary re-implementation of complex access logic while enabling integration with fast Julia libraries. The conceptual similarity between Julia and Python further reduces friction, allowing users to adopt these tools with minimal syntactic adaptation. Besides python-based tools, `IRBEM.jl` packages provide native bindings to established Fortran libraries while simplifying installation and cross-platform distribution through Julia’s package and binary management infrastructure. These interfaces expose both low-level library calls and higher-level abstractions suitable for interactive data analysis, enabling magnetic field models and coordinate transformations to be incorporated naturally into Julia workflows.

Figure B.2 presents a sample use case of contour detection of 2D images map for AIA data using `SunPy.jl`. In this workflow, The `sunpy` function `Fido`, an unified data search interface, provides the data acquisition and loading, while all subsequent analysis is performed in Julia. The data is directly memory-mapped to Julia arrays, and we utilize a Julia library `Contour` to perform the contour detection. This example achieves performance improvements of approximately 20 times faster compared to equivalent operations executed within Python. This example illustrates how interoperability enables Julia to function as a high-performance analysis layer atop existing community tools.

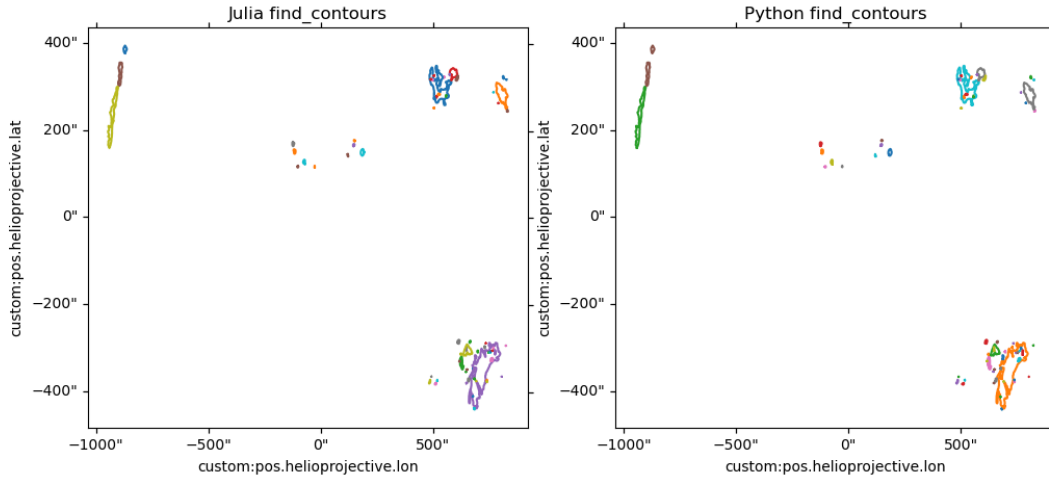


Figure B.2: Contour detection of AIA data using SunPy.jl

B.4.2 Julia-Native Implementations and Performance-Critical Kernels

As hybrid workflows matured, recurring performance bottlenecks became increasingly apparent, motivating the development of Julia-native implementations for core analysis routines. By reimplementing performance-critical components in Julia, the ecosystem can fully exploit just-in-time compilation, multiple dispatch, and native array semantics, while preserving a high-level and extensible programming model. Many commonly used analysis routines have therefore been translated from legacy implementations and refactored or rewritten entirely to improve both generality and performance. In many cases, these Julia-native versions are syntactically simpler and more flexible than their predecessors, while delivering substantial speedups.

A representative and nontrivial example is the Julia implementation of moment calculations provided by [VelocityDistributionFunctions.jl](#). This implementation achieves speedups of up to two orders of magnitude compared to Python-based implementations in PySPEDAS, while supporting a wide range of input data formats in a uniform and readable manner. Velocity distribution functions may be provided as either two-dimensional (energy, angle) or three-dimensional (energy, ϕ , ϑ) arrays, with energy binning that can vary across angles and time or remain fixed. Using [CartesianIndices](#), the Julia implementation expresses the underlying multidimensional algorithms directly, without

requiring data reshaping or separate code paths for different dimensionalities. The resulting performance gains arise from Julia’s ability to execute explicit loops at near-C speed. Unlike Python/NumPy, where performance typically depends on vectorization and the avoidance of explicit loops, Julia allows moment calculations of different orders to be fused naturally within a single loop. In Python, such loop fusion is difficult to achieve, often leading to repeated intermediate computations, less readable code, and reduced generality. In contrast, the Julia implementation simultaneously improves performance, clarity, and extensibility.

Similarly, a matrix-based plasma wave dispersion solver—originally developed in MATLAB—has been fully translated into open-source Julia implementations (Bai et al., 2025; Xie, 2025; 2014; Zhang, 2026). In addition to achieving performance improvements of approximately a factor of two, the Julia version introduces a unified interface supporting multiple solver formulations, including multi-fluid models, arbitrary or analytic kinetic distributions, and analytic Product-Bi-Kappa distributions. This unified design simplifies switching between physical models and significantly reduces code duplication, improving both usability and long-term maintainability.

Comparable improvements are observed across a broad range of commonly used analysis tasks (see Table B.3 for a summary of representative benchmarks). Coordinate transformations are approximately an order of magnitude faster than Fortran-based IRBEM routines (Boscher et al., 2022) and up to twenty times faster than their PySPEDAS counterparts. Minimum variance analysis achieves speedups of up to three orders of magnitude relative to Python implementations while also generalizing naturally to arbitrary dimensionality. Wave polarization analysis is accelerated by approximately $250\times$ compared to PySPEDAS (Santolík et al., 2003) benefiting from parallelization and optimized memory management that reduce repeated allocations and redundant computations. Magnetic field model evaluations for Tsyganenko models are $100\text{--}250\times$ faster than geopack (Tsyganenko, 1989), in part through lazy interpolation strategies. Multi-spacecraft analysis workflows, including spatial gradient estimation (Paschmann & Daly, 2008), similarly exhibit speedups of roughly two orders of magnitude by minimizing heap allocations and leveraging fused linear algebra operations. Across the JuliaSpacePhysics ecosystem, performance improvements of one to two orders of magnitude are typical for core computational routines, reflecting a

combination of just-in-time compilation, algorithmic refactoring, reduced memory allocation, and effective parallel execution.

Table B.3: Performance comparison between Julia-native implementations in the JuliaSpacePhysics ecosystem and commonly used reference implementations. Benchmarks were performed on identical datasets and hardware. Reported speedups represent median wall-clock runtime ratios (reference / Julia) over multiple runs.

Analysis Task	Julia Package	Reference Implementation	Speedup ($\times$)
Moment calculation (density, velocity, pressure tensor)	<code>VelocityDistributionFunctions.jl</code>	PySPEDAS (NumPy-based)	$\sim 100\times$
Minimum variance analysis (MVA)	<code>MinimumVarianceAnalysis.jl</code>	PySPEDAS	$\sim 1000\times$
Coordinate transformations	<code>GeoCotrans.jl</code> / <code>IRBEM.jl</code>	IRBEM (Fortran), PySPEDAS	10–20 $\times$
Wave polarization analysis	<code>WaveAnalysis.jl</code>	PySPEDAS	$\sim 250\times$
Tsyganenko magnetic field models	<code>Tsyganenko.jl</code> (via IRBEM bindings)	geopack	100–250 $\times$
Plasma wave dispersion solver	Julia dispersion solver	MATLAB version	$\sim 2\times$
Multi-spacecraft gradient estimation	<code>MultiSpacecraftAnalysis.jl</code>	PySPEDAS	$\sim 100\times$

B.4.3 Tplot

These performance gains directly enable new modes of interactive data exploration that were previously impractical due to computational cost. One illustrative example is the extended design of the tplot-style visualization interface, originally introduced in SPEDAS. In its IDL and Python implementations, Tplot primarily supports stacked time-series visualizations composed of line and spectrogram panels. In the Julia implementations,

this concept is generalized to support functions that operate directly on user-defined time intervals. This enables interactive plots in which data retrieval and derived quantities are computed on demand. This functionality is implemented using modern, high-performance plotting libraries such as Makie.jl (Danisch & Krumbiegel, 2021), allowing responsive interactivity and publication-quality figure generation within a unified framework.

Figure B.1 shows a demonstration of interactive analysis where we use multi-parameter solar wind data from the OMNI dataset. In this example, multiple physical variables are visualized simultaneously, while minimum variance analysis and associated coordinate transformations are computed dynamically and displayed alongside the original time series. Users can interactively adjust the temporal range of interest, triggering on-demand data loading and recomputation of derived quantities. Owing to aggressive caching strategies and efficient data access through Julia-based CDAWeb and SPEDAS interfaces, these interactions occur with minimal latency, enabling near real-time exploratory analysis.

Together, these capabilities illustrate how high-performance computation, combined with an interactive programming environment, enables not only faster data analysis but also qualitatively new scientific workflows. The JuliaSpacePhysics ecosystem therefore supports both efficient large-scale processing and interactive, hypothesis-driven research. Importantly, these performance gains enable entire classes of analyses that were previously impractical, rather than merely accelerating existing workflows. Such analyses include large parameter sweeps, on-the-fly visualization and diagnostic evaluation for large datasets, and large ensemble or statistical studies that were often avoided due to their computational cost.

B.5 Decentralized Development, Modular Architecture, and Ecosystem Sustainability

Another defining feature of the JuliaSpacePhysics ecosystem is its decentralized, modular, and layered software architecture. Rather than concentrating functionality within a single, monolithic codebase, individual capabilities—such as data access, calibration, analysis methods, and visualization—are implemented as independent, focused packages that

address well-defined tasks. This composable design allows each component to evolve autonomously while remaining interoperable through shared abstractions and well-defined interfaces.

This approach stands in contrast to the centralized architecture historically employed by systems such as SPEDAS in both its IDL and Python implementations. In those frameworks, mission-specific routines, calibration procedures, and data-processing pipelines are typically embedded directly within a unified package structure. While this model simplifies distribution and onboarding for end users, it can also lead to tightly coupled code, increased maintenance burden, and reduced flexibility as the scope of supported missions and instruments grows.

By contrast, the JuliaSpacePhysics ecosystem encourages decentralized development by establishing a small set of stable, extensible base APIs upon which higher-level packages can be built. New missions, instruments, or analysis techniques can be supported by developing independent modules that conform to these shared interfaces, without requiring modification of a central codebase. This separation of concerns not only improves maintainability but also lowers the barrier for community contributions, as developers can focus on domain-specific functionality within self-contained packages.

Several examples illustrate this structure. For example, mission-focused `DMSPData.jl` (Redmon et al., 2017; Zhang, 2025) provides convenient utilities for accessing and processing Defense Meteorological Satellite Program (DMSP) data (such as precipitating particle fluxes and plasma data), while `Madrigal.jl` serves as the foundational package for querying metadata and downloading files from the Madrigal Database. It is ready to use `IRBEM.jl` to compute magnetic field coordinates for conjunction study. Similarly, `ELFINData.jl` (as an example of a CDF-based loader) are built atop the ecosystem’s CDF handling libraries, which provide efficient access to CDF files and utilize `VelocityDistributionFunctions.jl` to derives directionally resolved flux spectra (omni, para, anti) and/or pitch-angle spectra.

In the heliospheric domain, packages dedicated to energetic particle (EP) analysis—such as `SolarEnergeticParticles.jl`—leverage lower-level data-access tools `Speasy.jl` to retrieve measurements from missions including Parker Solar Probe, Solar Orbiter, and STEREO via NASA CDAWeb. It contains onset determination analysis and velocity Dispersion

Analysis for determining solar particle release times and propagation characteristics by analyzing the energy-dependent arrival times of EPs. By relying on the shared I/O layer, these packages can focus exclusively on mission-specific variable conventions, derived products and analysis functions, without reimplementing file-format logic.

This decentralized model aligns well with the collaborative and evolving nature of space physics research. As new missions are launched and new analysis requirements emerge, the ecosystem can grow organically through the addition of interoperable modules, rather than through continual expansion of a single centralized framework. In this way, JuliaSpacePhysics provides a scalable and sustainable software foundation for long-term community-driven development.

B.6 Summary and Outlook

In this paper, we have introduced the JuliaSpacePhysics ecosystem, an effort to provide modern, high-performance tools for space physics data access, analysis, and visualization. By leveraging the capabilities of the Julia programming language—including just-in-time compilation, multiple dispatch, and abstract array interfaces—the ecosystem delivers accelerated data processing while preserving flexibility and interoperability with existing community infrastructure.

The ecosystem’s design philosophy emphasizes modularity, abstraction, and interoperability. Dedicated client packages provide access to major space physics data repositories, while high-performance I/O layers enable efficient handling of widely used formats such as CDF. Analysis routines are implemented against abstract interfaces rather than concrete data containers, allowing them to operate transparently across heterogeneous data formats and memory backends. This approach decouples file format, metadata standard, and computational representation, thereby facilitating integrative, multi-mission studies. The resulting architecture enables not merely improved execution speed, but entirely new scientific workflows: accelerated computation and efficient data access support interactive exploratory analysis, large-scale statistical studies, and parameter sweeps that would be computationally prohibitive in traditional environments.

Currently, the JuliaSpacePhysics ecosystem focuses on observational data analysis and does not yet support numerical modeling or large-scale simulation. Nevertheless, many of the abstractions and analysis interfaces developed here are sufficiently general to extend to simulation outputs. The same time series interfaces, coordinate transformation utilities, and analysis routines can naturally support model–data comparisons and advanced system-level studies.

Looking forward, continued community engagement and modular development will be essential for broadening mission coverage and expanding into simulation and modeling domains. By combining high performance, decentralized package design, and strong interoperability with existing tools, the JuliaSpacePhysics ecosystem provides a scalable and sustainable computational foundation for next-generation space physics research, particularly for processing data from multi-spacecraft and high-cadence missions.

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