Exploring solar wind discontinuity properties in the inner and outer heliosphere

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Abstract

Solar wind discontinuities, characterized by abrupt changes in the magnetic field, play a crucial role in heliospheric dynamics, such as solar wind heating and turbulence. This proposal aims to conduct a detailed study of these discontinuities, leveraging data from contemporary space missions like Parker Solar Probe (PSP) and Juno to examine their characteristics (occurrence rates, thickness, current density, etc.) from the Sun to beyond 1 AU. By analyzing the evolution of these features, this study seeks to answer questions about how the discontinuities change with the radial distance from the Sun and the physical mechanisms behind the formation of solar wind discontinuities. Additionally, this research will explore ion and electron dynamics associated using hybrid and particle-in-cell (PIC) simulation to understand their role in formation and evolution of discontinuities. The integration of observational data from multiple spacecraft with advanced modeling techniques will shed light on the complex interactions within solar wind discontinuities, enhancing our understanding of heliosphere.

Introduction and Background

The study of solar wind magnetic discontinuities, characterized by rapid variations in interplanetary magnetic fields, stands at the forefront of understanding key phenomena in Heliophysics. These discontinuities, manifesting as localized transient rotations or jumps in the magnetic field, are pivotal in processes such as efficient plasma heating and in hosting plasma instabilities associated with discontinuity currents, which are among the most intense currents in the solar wind. Theoretical models suggest that the formation and destruction of discontinuities are closely related to the nonlinear dynamics of Alfvén waves. These nonlinear processes can create significant isolated disturbances to the otherwise adiabatic evolution of the solar wind flow. Investigatation of the nonfluid (kinetic) properties of solar wind discontinuities reveals that electron density and temperature vary significantly across these discontinuities, underlining the importance of kinetic effects in discontinuity structure.

As such, this study aims to understand the dynamics of solar wind discontinuities by addressing the key question

"How do discontinuities evolve over radial distances from the Sun and what are the physical mechanisms behind their formation and evolution?"

Understanding these discontinuities is essential for elucidating the fundamental processes that govern the solar wind's evolution as it travels through the heliosphere.

Previous Studies and Context

Spacecraft investigations of the space plasma environment have revealed that the solar wind magnetic field follows the Parker model of the heliospheric current sheet only on average. Localized transient currents, that can be significantly more intense than the model currents, are carried by various discontinuities observed as strong variations in magnetic field components [Colburn and Sonett, 1966, Burlaga, 1968, Turner and Siscoe, 1971]. Most often such variations are manifested as magnetic fieild rotations within the plane of two most fluctuating components.

Further advancements were made with data from the Helios-1, Helios-2, Ulysses and Voyager missions, which explored discontinuities in three-dimensional space, revealing their prevalence and importance throughout the heliosphere [Mariani et al., 1983, Tsurutani et al., 1997]. As illustrated in Figure 1, these discontinuities are observed at a multitude of radial distances from the Sun. These findings underscored the need to understand the origin of discontinuities, which are thought to arise from dynamic processes on the Sun, including solar flares and coronal mass ejections, as well as through in-situ processes like local magnetic turbulence, magnetic reconnection and nonlinear wave interactions within the solar wind.

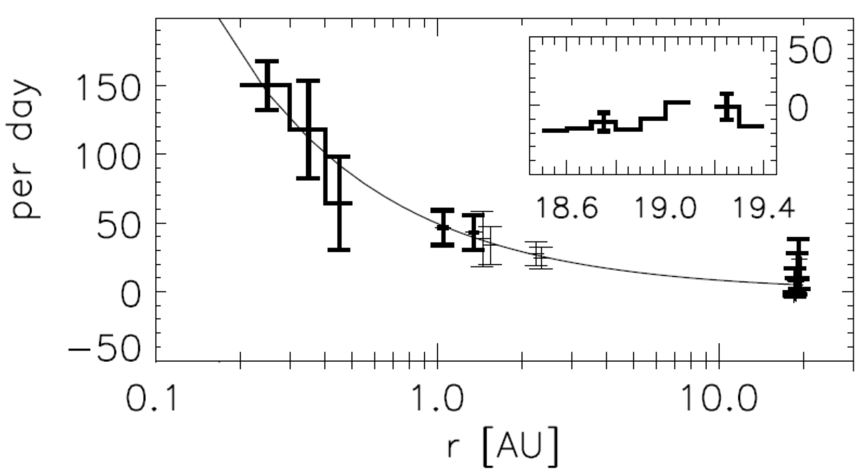


Figure 1: Distribution of occurrence rate of solar wind discontinuities [Söding et al., 2001].

The Role of Alfven wave and kinetic effects in the discontinuities

Ulysses measurements of the high-latitude solar wind at $1-5$ AU showed that the majority of discontinuities resided within the stream-stream interaction regions and/or within Alfvén wave trains [Tsurutani et al., 1995, Tsurutani and Ho, 1999]. The nonlinear evolution of Alfvén waves (wave steepening) can be the main cause of such discontinuities. The background plasma/magnetic field inhomogeneities and various dissipative processes are key to Alfvén wave nonlinear evolution [**?????**]. In hybrid simulations [see **???**] and analytical models [e.g., **?????**], this steepening was shown to cause formation of discontinuities in configurations resembling the near-Earth observations. There are models predicting discontinuity formation [**??**] and destruction [**??**] due to dissipative processes (e.g., Alfvén wave steepening, magnetic reconnection) in the solar wind. However, the efficiency of these processes in realistic expanding solar wind was not yet tested against observations.

More recently, utilizing high-resolution plasma measurements from ARTEMIS and MMS missions, Artemyev et al. [2019] showed that discontinuities have kinetic characteristics for both tangential and rotational discontinuities: fluxes of electrons of different energies vary differently across these discontinuities. This discoveries revealed the importance of ion and electron kinetics to discontinuity structure.

Current Gaps in Understanding

Previous observations of solar wind discontinuities in the outer heliosphere were rarely in conjunction with measurements closer to the Sun. Thus it is presently unclear whether their frequency and properties are the result of solar variability or due to the natural evolution of the discontinuities during their propagation and interaction with the ambient solar wind.

Regular and long-lasting Juno (2011-2016) and PSP (2019-now) observations together with almost permanent near-Earth solar wind monitoring provide a unique opportunity to examine the discontinuity characteristics at two radial distances simultaneously in the context of both the inner and in the outer heliosphere over an large radial distance range ($\sim$ 0.1 AU - $\sim$ 5 AU). We will determine the discontinuity occurrence rates and properties for various radial distances and compare these results with the prediction of the adiabatic expansion model, **to understand if discontinuity formation or destruction dominate the statistics of discontinuities far away from the solar wind acceleration region**.

In addition, with the increasing computational resources and advanced numerical techniques on GPU-accelerated platforms [Myers et al., 2021], it is now possible to simulate the solar wind discontinuities with full kinetic effects included using PIC code. The kinetic simulations will be used to **understand the role of ion and electron kinetics in the formation and evolution of discontinuities**.

This research seeks to address these gaps by leveraging recent advancements in observational capabilities and numerical modeling to provide a comprehensive examination of solar wind discontinuities.

Methodology

Data Collection:

- **Parker Solar Probe** and **Juno**: These spacecraft provide high-resolution magnetic field and plasma data from the inner heliosphere to beyond 1 AU. The PSP's close passes to the Sun offer unique insights into the nascent solar wind, while Juno's trajectory up to Jupiter allows for studying the evolution of solar wind structures as they propagate outward.
- Complementary Data from Other Missions: Data from missions like STEREO, ARTEMIS, and WIND will complement PSP and Juno observations, providing a broader contextual view of the heliospheric conditions and enabling a multi-point analysis of discontinuity properties [Velli et al., 2020].

Proposed Approach:

This first step in understanding the evolution of solar wind discontinuities involves identifying and characterizing these structures. We will adopt Liu's method [Liu et al., 2022] for this purpose, as it demonstrates better compatibility with discontinuities exhibiting minor field changes and is more robust to the situation encountered in the outer heliosphere. Then for each discontinuity identified, we calculate the distance matrix of the time series sequence (distance between each pair of magnetic field vectors) to determine the leading edge and trailing edge of the discontinuity. After that, we will utilize the minimum or maximum variance analysis (MVA) analysis [Sonnerup and Scheible, 1998, Sonnerup and Cahill Jr., 1967] to determine the main (most varying) magnetic field component, B_l, and medium variation component, B_m. The maxium variance direction is then fitted by a step-like functions to extract the parameters to properly describe the discontinuity (we used logistic function here $B(t; A, \mu, \sigma, \text{form} = \text{logistic}) = A\left[1 - \frac{1}{1+e^{\alpha}}\right]$, where $\alpha = (t-\mu)/\sigma$). Examples of solar wind discontinuities detected by various spacecraft are illustrated in Figure 2.

Two promising approaches are proposed for studying the evolution of solar wind discontinuities: **1. Conjunction Events Analysis:** This approach involves studying instances where spacecraft are either simultaneously aligned along the same spiral field line, thus measuring solar wind emanating from the same solar surface region, or positioned to measure the same solar wind plasma [Velli et al., 2020]. The latter alignment is determined by the difference in radial distance, δR, corresponding to the solar wind travel time, $\tau = \delta R/V_{sw}$. An example demonstrating this approach is presented in Figure 3, showcasing similar trends in magnetic field magnitude, plasma density, velocity, and temperature observed by the Parker Solar Probe (PSP) and the Advanced Composition Explorer (ACE) during an alignment period in April

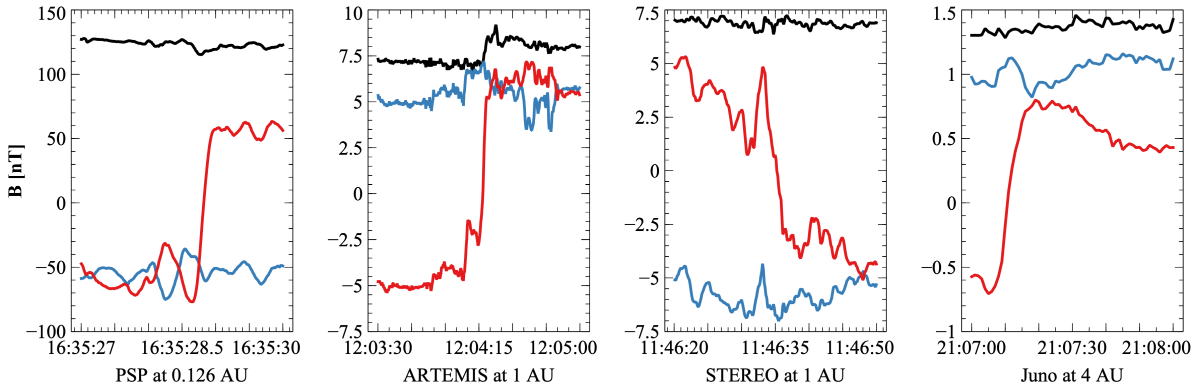
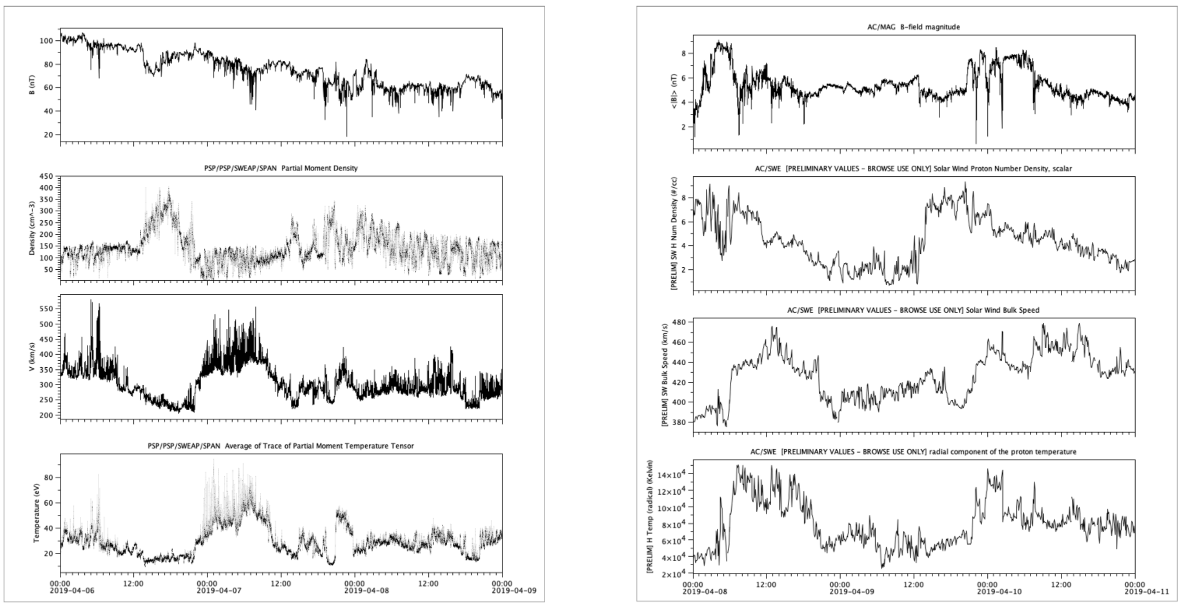


Figure 2: Discontinuities detected by PSP, Juno, STEREO and near-Earth ARTEMIS satellite: red, blue, and black lines are B_l, B_m, and $|\mathbf{B}|$.

2019. Validation is further supported by utilizing the statistical plasma expansion model [Perrone et al., 2019], where the plasma properties measured by PSP and projected to the ACE location exhibit good agreement with actual ACE measurements, as depicted in Figure 5. This confirms the validity of the alignment approach for studying solar wind discontinuities. **2. Comparative Analysis:** This approach leverages extensive data collected over the years to compare solar wind discontinuities observed by different spacecraft at various radial distances. Due to the Sun's rapid rotation, solar wind plasma emitted from a single region on the solar surface sweeps across the entire heliosphere within a solar rotation period of 27 days. By utilizing solar wind measurements at 1 AU from STEREO, ARTEMIS, and WIND, and comparing these with data from Juno and PSP, it is possible to distinguish between the effects of temporal variations in solar wind and those due to spatial variations (associated with radial distance from the Sun) in the occurrence rate and characteristics of discontinuities. An example of such a comparison for the occurrence rate is depicted in Figure 4, where the number of discontinuities measured per day by different spacecraft missions is plotted.

In the proposed study, we will expand this comparison to include the properties of discontinuities, such as thickness, strength (current density), and orientation.

This extension will enable us to grasp how these features evolve with radial distance from the Sun and how they relate to the local plasma properties. Examining these properties is crucial for understanding the generation of discontinuities. Borovsky [2008] argued that solar wind discontinuities act as static boundaries between flux tubes originating at the solar surface and they are convected passively from the source regions. However, Greco et al. [2009], by examining the waiting time distribution of magnetic field increments, discovered a good agreement between between MHD simulations and observations. This finding suggests that discontinuities stem from intermittent MHD turbulence, indicating local generation. If turbulence theory holds true, discontinuities properties should align with local plasma parameters; conversely, if propagation theory is accurate, discontinuities properties should be consistent with solar wind



PSP observation **ACE observation**

Figure 3: Measurement by PSP and ACE spacecrafts from 2019-04-06 to 2019-04-10. From top to bottom: (a) Magnetic field magnitude measured (b) Plasma density, (c) Plasma velocity, (d) Plasma temperature.

expansion model. Studying these properties will provide insights into the physical mechanisms governing discontinuity formation and spatial evolution as solar wind propagates through the heliosphere.

Summary

This research project will employ a comprehensive approach to dissect the complex nature of solar wind discontinuities, offering insights into their fundamental properties and impacts across the heliosphere. By integrating observational data with theoretical analyses and numerical simulation, this research aims to unravel the intricate processes that govern the magnetic discontinuities, the key element of magnetic field turbulence and the primary interface of charged particle acceleration.

Figures

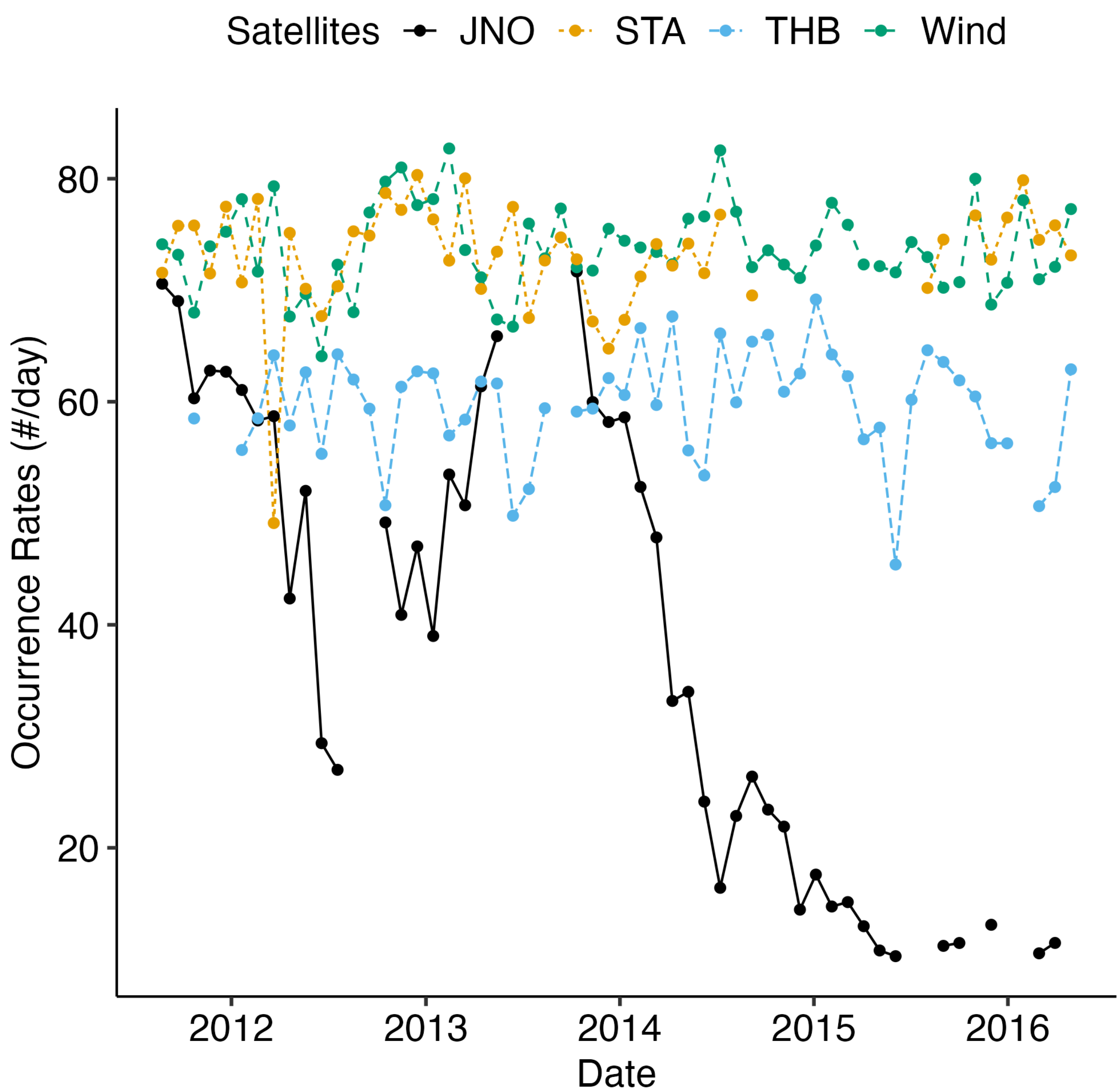


Figure 4: The number of discontinuities measured by Juno per day coincides with the discontinuity number measured by STEREO, WIND, and ARTEMIS, when Juno is around 1 AU. This number (occurrence rate) decreases with distance (with time after ~ 2013), as Juno moves from 1 AU to 5 AU. We will use the similar comparison for discontinuity characteristics and occurrence rate derived for PSP and Juno.

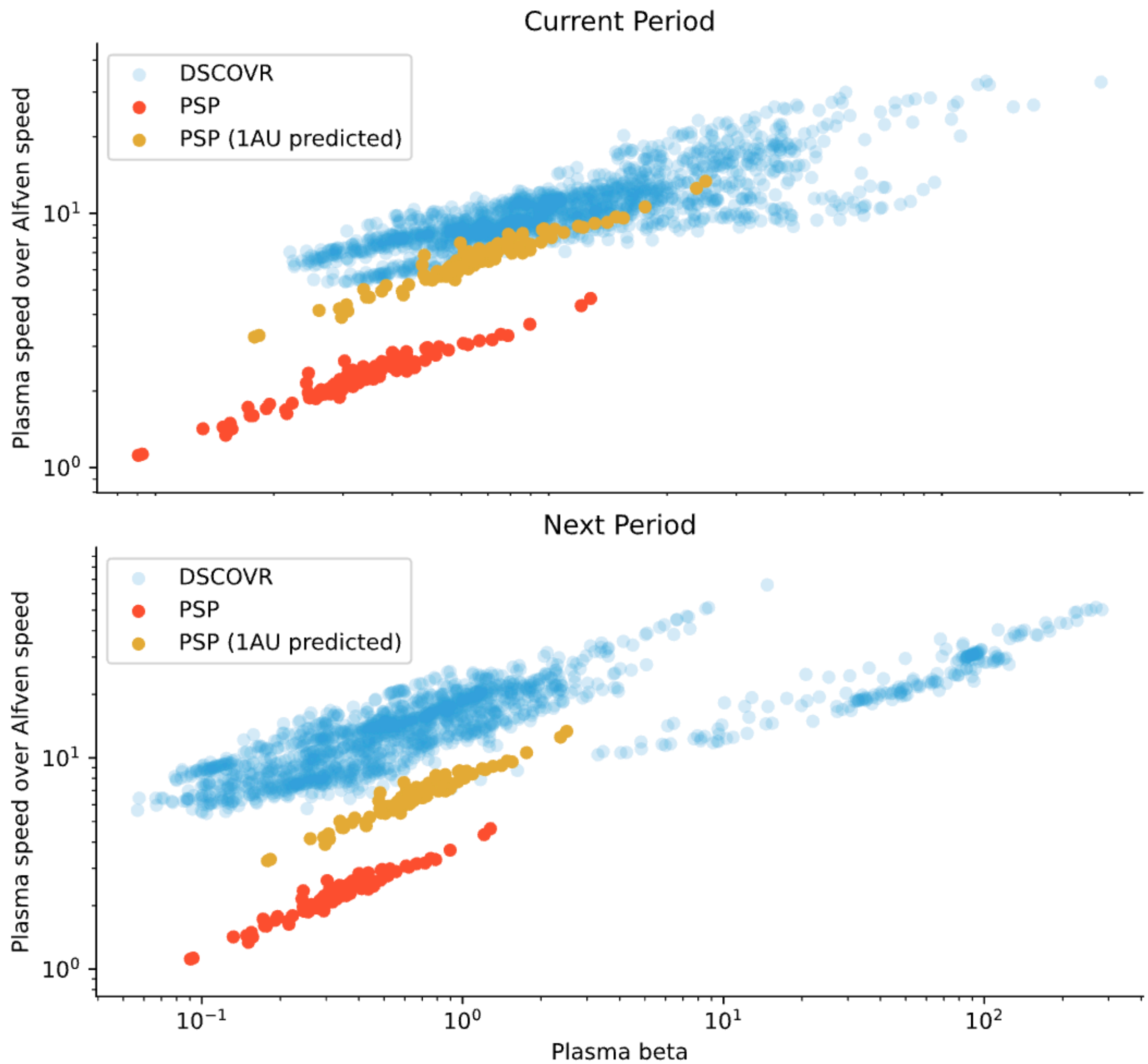


Figure 5: Plasma properties (plasma beta versus plasma speed normalized by Alfven speed) measured by PSP projected to the ACE location using the statistical plasma expansion model. Top panel shows the data from the candidate alignment period (2019-04-06 to 2019-04-07) and the bottom panel shows the data after the alignment period.

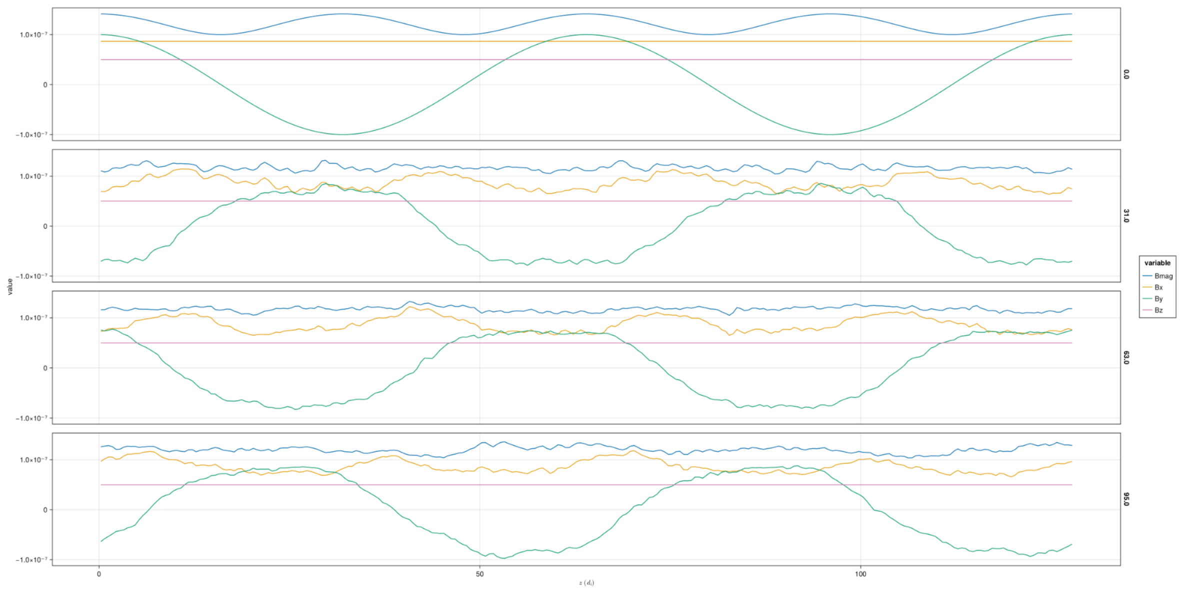


Figure 6: Formation of a rotational discontinuity in the solar wind, reproduced using hybrid simulation. The magnetic field components B_x, B_y, B_z, magnetic field magnitude $|\mathbf{B}|$ are shown in different colors, with each panel corresponding to different times in the simulation normalized by the ion cyclotron period.

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