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Evolution and Sources of Switchbacks Observed in the Solar Wind

Évolution et sources des switchbacks observés dans le vent solaire

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Résumé

Les observations récentes de la sonde Parker Solar Probe (PSP), lancée en 2018, apportent des données inédites sur l'origine du vent solaire. L'objectif scientifique de la mission est de révéler les mécanismes physiques au plus proche du Soleil qui seraient reliés à deux questions fondamentales, le problème du chauffage et de l'accélération du vent solaire. La mission a révélé l'omniprésence de déflexions soudaines du champ magnétique du vent solaire, les « switchbacks ». Ces structures, qui se propagent à la vitesse d'Alfvén, pourraient être à la source de transferts d'énergie qui répondraient à ces questions. À ce jour, leur origine ainsi que leur capacité à survivre dans le vent solaire restent à élucider.

Je vais présenter le travail accompli durant cette thèse dans le but de comprendre l'origine et l'évolution des switchbacks à partir de mesures in situ du champ magnétique ainsi que des observations par télédétection. Dans un premier temps, je me concentre sur la nature des frontières des switchbacks, qui sont l'intervalle pendant lequel se produit la majeure partie de la déviation du champ magnétique. En raison de la complexité de la structure 3D de ces frontières, leur analyse nécessite la définition d'une nouvelle méthodologie. Je montre que leur nature correspond à des structures fermées. Ce nouveau résultat suggère que l'érosion des switchbacks est plus faible que prévu. Cela pourrait expliquer leur présence à de grandes distances du Soleil. Ce résultat est aussi compatible avec une origine des switchbacks dans la basse atmosphère du Soleil, ce qui motive la seconde partie de ma thèse, qui se concentre sur l'origine des switchbacks. Il existe plusieurs hypothèses non-exclusives quant à leur origine. Cependant, il y a actuellement un consensus sur le rôle joué par de petits événements de reconnexion dans la basse couronne du Soleil dans la création des conditions nécessaires à la génération des switchbacks. Cette hypothèse n'a pas encore été confirmée, en raison de la difficulté de connecter les événements transitoires dans la couronne aux structures se propageant dans le vent solaire. L'objectif de cette étude est d'établir, statistiquement et à partir d'observations, si des jets de points brillants coronaux localisés dans des trous coronaux peuvent être des précurseurs des switchbacks observés in situ par le satellite. Bien que cette étude soit la plus détaillée à ce jour, les résultats ne montrent pas de corrélation claire. Différentes raisons sont envisagées pour l'expliquer. Les modèles établis ne seraient pas suffisamment précis pour étudier les petits événements éruptifs ce qui nécessiterait une analyse plus fine de la configuration magnétique dans la basse couronne. Les résultats pourraient aussi être influencés par notre compréhension limitée des processus évolutifs qui se sont déroulés au cours de la propagation du vent solaire. L'étude d'un éventail plus large d'événements éruptifs et non limité aux jets pourrait aussi être nécessaire pour identifier les événements précurseurs des switchbacks.

Abstract

Recent observations by the Parker Solar Probe (PSP) mission, launched in 2018, provide new clues on the origin of the solar wind. The scientific goal of the mission is to reveal the physical mechanisms closest to the Sun that are linked to two fundamental and unresolved questions, the problem of heating and acceleration of the solar wind. The mission revealed the ubiquity of sudden deflections of the solar wind's magnetic field, known as switchbacks. These structures, which propagate at the Alfvén speed, could be the source of energy transfers that answer these questions. Their origin and their ability to survive in the solar wind have yet to be elucidated.

The work carried out in this thesis aims to understand the origin and evolution of switchbacks based on both in situ magnetic field measurements and remote sensing observations. First, I focus on the nature of switchback boundaries, the intervals that include most of the magnetic field deflection. Due to the complex 3D structure of these boundaries, their analysis requires the definition of a new methodology. I show that the nature of the boundaries corresponds to closed structures, which is a new result. This has an implication on the propagation of switchbacks, as the results suggest that their erosion may be much slower than expected. This, in turn, may explain why we observe switchbacks far from the Sun. The results are also compatible with an origin of switchbacks that is rooted in the lower solar atmosphere, which motivates the second part of my thesis. There are various non-exclusive hypotheses as to the origin of switchbacks, including an origin in the Sun's lower atmosphere. Nevertheless, there is currently a consensus on the role that small reconnection events play in the Sun's lower corona in creating conditions for generating switchbacks through magnetic reconnection. This hypothesis has yet to be verified due to the difficulty of relating transient events in the corona with structures propagating in the solar wind. The aim of this study is to establish, statistically and through observations, whether jets from coronal bright points located in coronal holes can be precursors of switchbacks. Although this study is the most detailed approach to date, the results show no clear correlation. Different reasons are considered. The implemented models would not be precise enough to study the small-scale eruptive events, that would require a finer analysis of the magnetic topology in the lower corona. Evolutionary changes during solar wind propagation could affect our findings. It could also mean that a wider range of eruptive events, not just jets, might be the precursors of switchbacks.

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Introduction

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1.1 Global context and Fundamental questions

1.1.1 The Solar Atmosphere

This journey begins with the Sun, the star of the Solar system, in which many planets orbit. From the Earth's ground, we mainly observe its 'surface', called the photosphere,

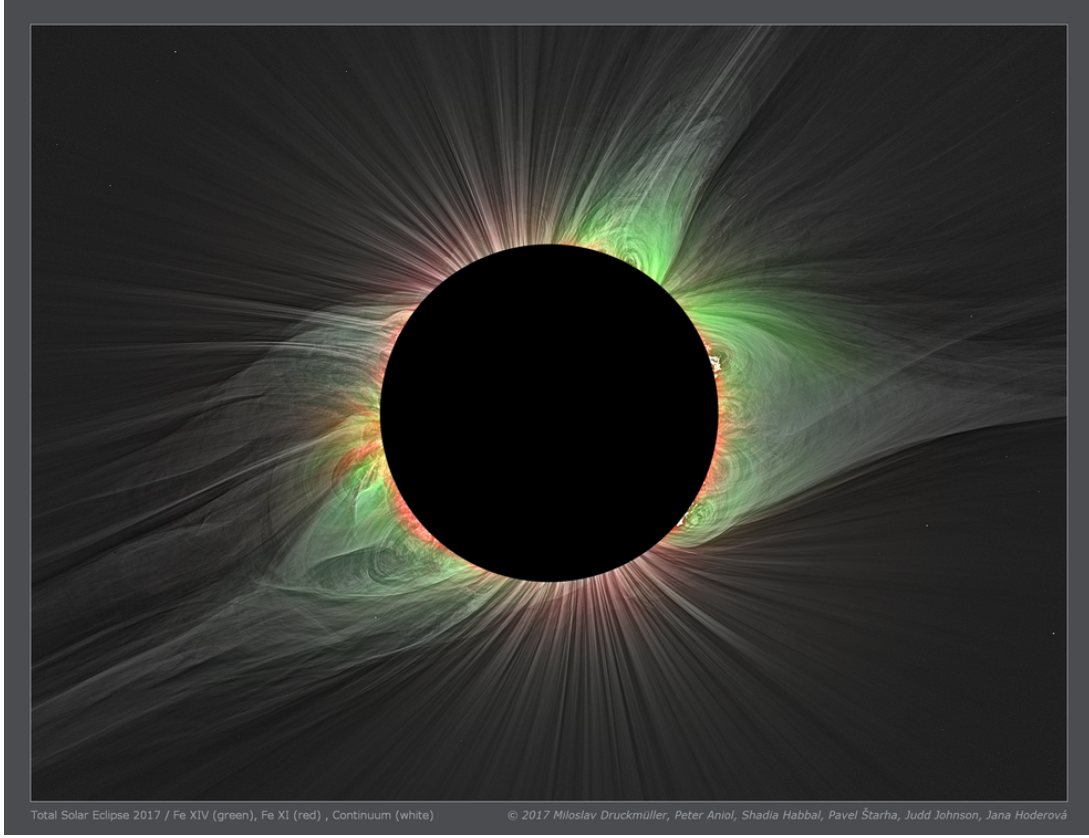


Figure 1.1: Eclipse image combining different filters, observed in Mitchell, Oregon, on August 21, 2017. Published in [Habbal et al. \[2021\]](#).

which emits the light we receive. This layer also comprises the lowest layer of the solar atmosphere. Although the photosphere is observable most of the time, observations of the upper atmosphere are more complex. They become possible during a solar eclipse when the moon hides the bright solar surface. This enables the observation of dimmer structures beyond the surface. Figure 1.1 reveals the corona with its complexity during a solar eclipse. The structures we observe are composed of plasma and a guiding magnetic field. In fact, the field lines and the particles are forced to move together, respecting the “frozen-in” theorem. The question that directly arises from that statement is to determine which of the plasma or the field is frozen in the other.

The discussion of the frozen-in theorem is usually done by means of the ratio of the thermal to magnetic pressure, which can help determine which of the plasma or the field dominates over the other. The ratio, called plasma β , is defined as:

$$\beta = \frac{nk_B T}{\left(\frac{B^2}{2\mu_0}\right)}, \quad (1.1)$$

where T is the temperature, n the particle density and B the magnetic field.

When $\beta \gg 1$, the plasma motion forces the magnetic field movement. In contrast,

when $\beta \ll 1$, the magnetic field drives the plasma motion so that the particles follow the field lines. In the solar corona, the magnetic field dominates, as observed in Figure 1.2, with $\beta < 1$. In the description of the image that will follow, the lines mentioned always refer to the emission from the frozen-in plasma that follows the field lines and not to the observation of the magnetic field itself. The first conclusion is that low plasma β leads to the complex structures observed in Figure 1.1. The apparent lines that are observed in the image highlight the magnetized nature of the body.

The magnetic topology impacts not only the close environment of the Sun but also the full heliosphere. Indeed, the Sun's magnetic activity expands in the interplanetary space up to distances about 100 au. The solar system planets are then surrounded by electromagnetic fields originating from the Sun. The combination of the electromagnetic field and particles frozen in the field forms the so-called solar wind, which I will introduce next. The subject of solar wind origin, acceleration, and properties has a number of open questions that are still intensively investigated.

The discussion on the solar wind mysteries will come soon, but first, let us dive into the substructures of the corona, as observed in Figure 1.1. One type of structure observed in the image of Figure 1.1 is closed loops, seen mainly in green. The plasma frozen in the field lines of these loops shows that the lines appear connected to the surface. One can clearly observe that the topology of the solar upper atmosphere, the corona, is complex, with overlying loops that reach different altitudes. Interestingly, the outermost part of the loop regions is composed of field lines that extend beyond the limit of the image, which gives the appearance of open field lines that extend into the interplanetary space. This open field allows particles to escape the solar atmosphere. The most striking observation of the open field is close to the poles, seen in red in the image. The field lines in these polar regions are all open to the interplanetary space, with a relatively simpler magnetic topology. The polar regions are dominated by open field lines, whereas the other latitudes are composed of a mix of open and closed field lines.

The complexity of the Sun lies not only in its magnetic topology but also in its atmospheric temperature profile. The primary origin of the Sun's thermal energy is located within its core and is due to a fusion process where hydrogen nuclei combine to form helium nuclei. Although several solar interior processes are necessary to bring the heat to the surface, I will not describe them here and will focus on the solar atmosphere hereafter. The bottom layer, the photosphere, has a temperature of about 5800 K. Knowing that the second law of thermodynamics states that the temperature should decrease as moving away from the heat source, one would logically expect to observe a decrease in the temperature with increasing altitude over the surface. In the solar context, the temperature profile of the solar atmosphere, presented in Figure 1.3, shows an abrupt temperature increase in the atmosphere, with multiple orders of magnitude over the photospheric temperature. The temperature in the corona reaches extreme temperatures of the order of 10^6 K. This is a surprising observation. The increase occurs in the region of the solar atmosphere called the transition region, which separates the cooler chromosphere from the hotter corona. The chromosphere is the layer of the

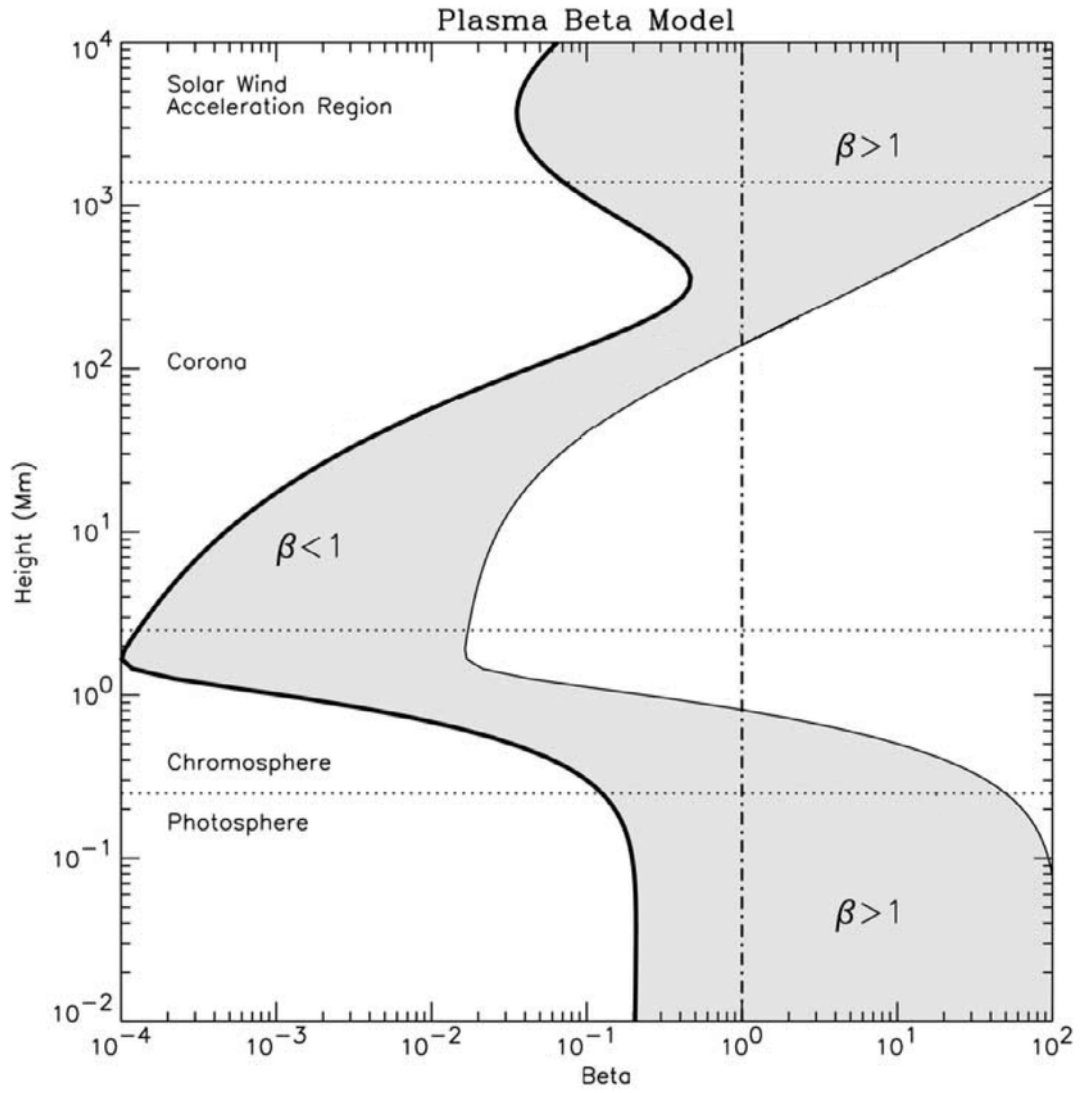


Figure 1.2: Plasma β in the different layers of the solar atmosphere, displayed as a function of height. Reproduced from [Gary \[2001\]](#).

Sun with the lowest temperature. This unexpected temperature increase in the solar atmosphere has been under intense investigation for several decades and has been the main scientific objective of numerous space missions and subsequent studies.

The consensus within the scientific community is that all mechanisms capable of heating the corona are linked to the convective movements occurring in the photosphere [e.g., [Arregui and Van Doorsselaere, 2024](#)]. The mechanisms are typically classified based on their timescales compared to the time taken by the fastest waves to cross a coronal structure, the Alfvén transit time τ_A . When the timescale is longer than τ_A , the driver is associated with magnetic structures and is called a DC heating mechanism. When the timescale is shorter than τ_A , the driver is associated with waves and is called an AC heating mechanism. The DC mechanisms are mainly based on the driving of magnetic field lines by the photospheric convection. The field is disturbed but always tends to return to its initial potential form. This creates a build-up of currents and a braiding of the field lines [[Parker, 1972](#)]. The currents may dissipate the magnetic energy, but the timescales are too small to explain the heating of the corona. That will require additional processes, such as reconnection between braided field lines [[Arregui and Van Doorsselaere, 2024](#)]. The AC mechanisms occur when the timescales are short so that the photospheric convection motions generate waves. Waves can transmit the energy generated at the photosphere to the corona, where it can be converted to heat. Secondary mechanisms are necessary to transport the wave energy to shorter scales, as the initial dissipation scale would not explain the heating of the corona [[Arregui and Van Doorsselaere, 2024](#)].

The study of the solar atmosphere and, more particularly, the corona is challenging, with multiple obstacles. The main issues are the short time scales and small spatial scales of the phenomena occurring in the solar corona. These scales are challenging to capture in the observations but also add difficulties in modeling the coronal heating. As discussed before, there is also a wide range of temperatures to cover for fully resolving the coronal plasma. Thus, it would require instruments that can resolve the spatial and temporal scales of the heating mechanisms at different temperatures.

1.1.2 The Solar wind

Historically, the first observation of the solar wind was from the observations of comet tails, geomagnetic storms, and auroras. Figure 1.4 presents an image of a comet that came close to the Earth in 1997. Two features are observed in the image. First, the bright white tail is composed of dust and volatile material vaporized and released when the comet approaches the Sun. A second tail, fainter, in blue on the image, has a different origin. The tail is sharper and is always oriented anti-sunward [[Biermann, 1963](#)]. This suggested to early astronomers a likely connection to the Sun. The tail is the result of the ionization of the comet particles due to the interactions with the solar-emitted particles.

Although comet tail observations were possible from Earth, in situ measurements were only possible following the space race during the Cold War. For the purpose of

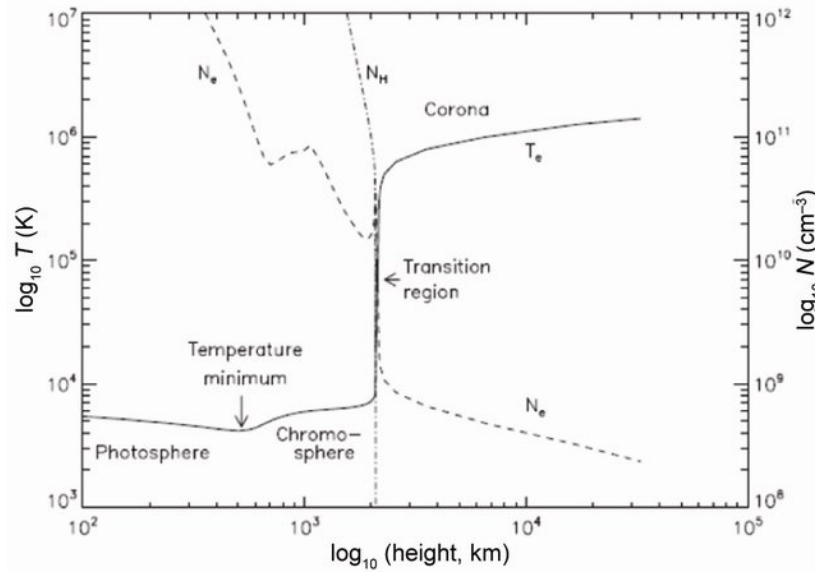


Figure 1.3: Temperature and density profiles in the solar atmosphere as a function of height. Reproduced from [Aschwanden \[2005\]](#).

ensuring human safety on the Moon, an uncharted territory, it was imperative to deploy instruments that could measure the lunar environment. That is the historical context in which the solar wind was first measured in situ. The Luna 1 probe provided the first solar wind measurements in the interplanetary space [[Gringauz et al., 1962](#)]. This achievement, however, was the result of an error. The mission was initially intended to crash-land on the Moon. After an orbital error, it orbited the Sun and provided in situ measurements of the solar wind outside the Earth's magnetosphere [[Gringauz, 1963](#)]. The instrumentation was limited, but it opened the way for future studies of the solar wind, which also led to the present work. The solar wind journey continued with measurements of Mariner 2.

[Neugebauer and Snyder \[1966\]](#) reported the first in situ measurements of the solar wind and its properties. They detected continuous streams of plasma with high activity following low activity intervals for a duration of 104 days. The velocity varied between 400 km s^{-1} and 700 km s^{-1} , and sometimes reached 1250 km s^{-1} . The numerous measurements allowed us to gain increasing knowledge of the solar wind. If we consider the discoveries during that period, the observations were almost made at the same time as the development of the theory. Indeed, in 1958, a few years before the Luna 1 mission, Eugene Parker theorized that the hot corona could not be in static equilibrium. It must continually expand into the interplanetary space, as the interstellar pressure is too low to contain a static corona. Using the steady state hydrodynamic equations and neglecting the electromotive forces except for gravity while considering an isothermal expansion and radial symmetry, the only feasible solution of the model was a function of the radius [[Parker, 1958](#)]. That solution is illustrated in Figure 1.5, with



Figure 1.4: Image of comet C/1995 O1, Hale-Bopp. Courtesy E. Kolmhofer, H. Raab; Johannes-Kepler-Observatory, Linz, Austria

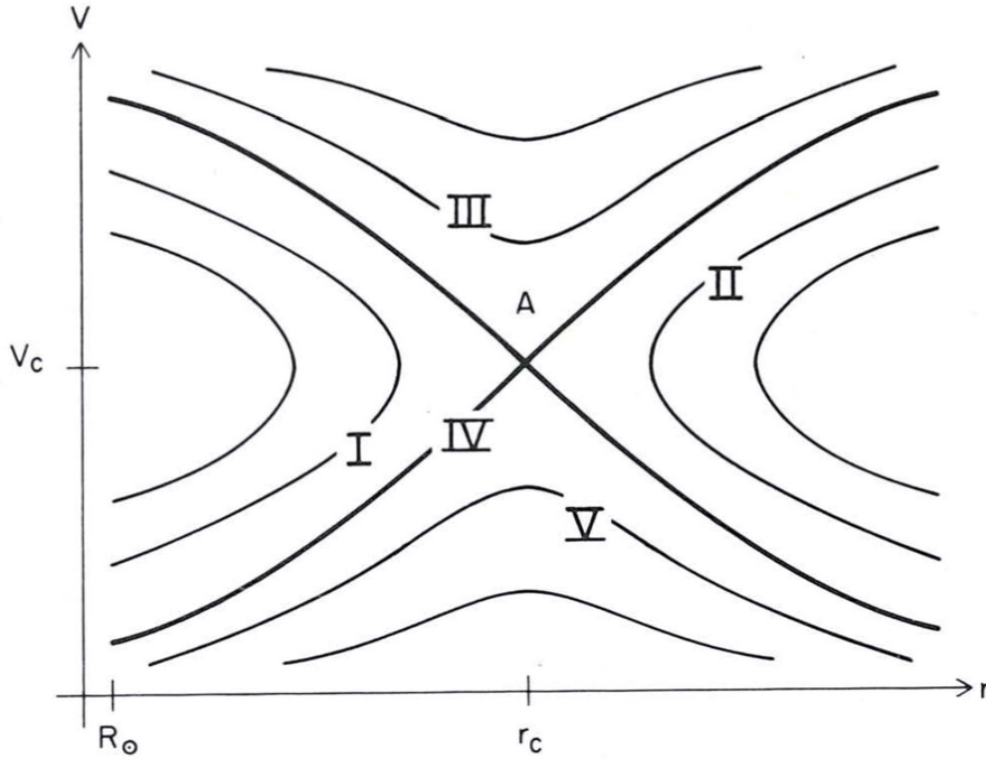


Figure 1.5: Sketch of the Parker isothermal solutions. It shows different types of winds. Type IV corresponds to the solar wind solution. Adapted from [Priest \[1982\]](#).

solution IV. Indeed, Eugene Parker predicted that it would generate a flow that would become supersonic at a distance of a few solar radii from the Sun, named the sonic point.

The solar wind is a stream of particles continuously emitted from the Sun that is intrinsically related to the magnetic field, so both should be studied coordinately. The wind is an ionized plasma that blows in interplanetary space and extends beyond the Earth's orbit to the interstellar space [[Baumjohann and Treumann, 2012](#)]. It is mainly composed of ionized hydrogen and electrons, with fewer ionized helium nuclei and heavier ions.

The typical velocity of the solar wind ranges between 300 and 1400 km s^{-1} , with a most probable value of 500 km s^{-1} . Originally, the streams were divided into two classes: the slow solar wind with velocities of less than 400 km s^{-1} and the fast solar wind with velocities higher than 600 km s^{-1} [[Baumjohann and Treumann, 2012](#)]. However, this distinction is a simplified picture of the solar wind and is currently being challenged with more complex winds, such as slow Alfvénic winds [[Perrone et al., 2020](#)]. Initially, the duality of the types of wind was associated with distinct solar source regions. The current understanding in the community leads to the interpretation that the source region plays a role in the type of wind, but the release processes, as well as how

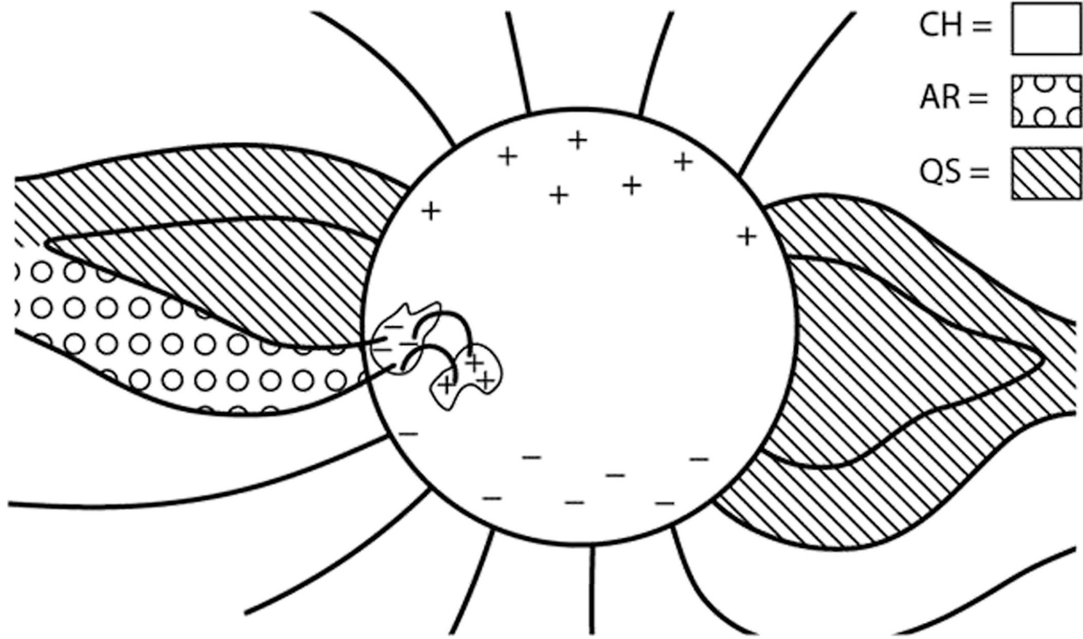


Figure 1.6: Cartoon presenting the different solar source regions of the solar wind. The three categories are CHs, ARs, and the QS. The streamer can be composed of plasma from QS only or could be mixed with plasma from AR. Reproduced from Viall and Borovsky [2020].

the plasma is accelerated, shape the wind and give different types of wind [Viall and Borovsky, 2020]. I will first discuss the source regions from which the solar wind originates.

1.1.3 Solar wind origin

The origin of the solar wind is one of the fundamental questions of the solar and solar wind physics. Indeed, the solar wind has been studied extensively, but surprisingly, the locations from which the slow solar wind originates are still unknown [Abbo et al., 2016]. The first certitude is that the solar wind, and thus all types of wind, originates from the solar atmosphere. Then, the substructures of the atmosphere should be introduced to set the context for the solar wind origin. There are three main categories of source regions, illustrated in Figure 1.6: the quiet Sun (QS), the coronal hole (CH), and the active region (AR). Each shows distinct properties in the Extreme Ultra Violet (EUV) emission that allow for classification. I will introduce each region using an EUV image for context, presented in 1.7.

First, a CH is a type of region that is observed throughout the solar cycle. In the context image, the CHs correspond to the dark areas when observed in EUV. CHs are usually found at the poles, but some CHs also exist closer to the equator. A CH is cooler and less dense, producing less EUV emission than the rest of the corona. That

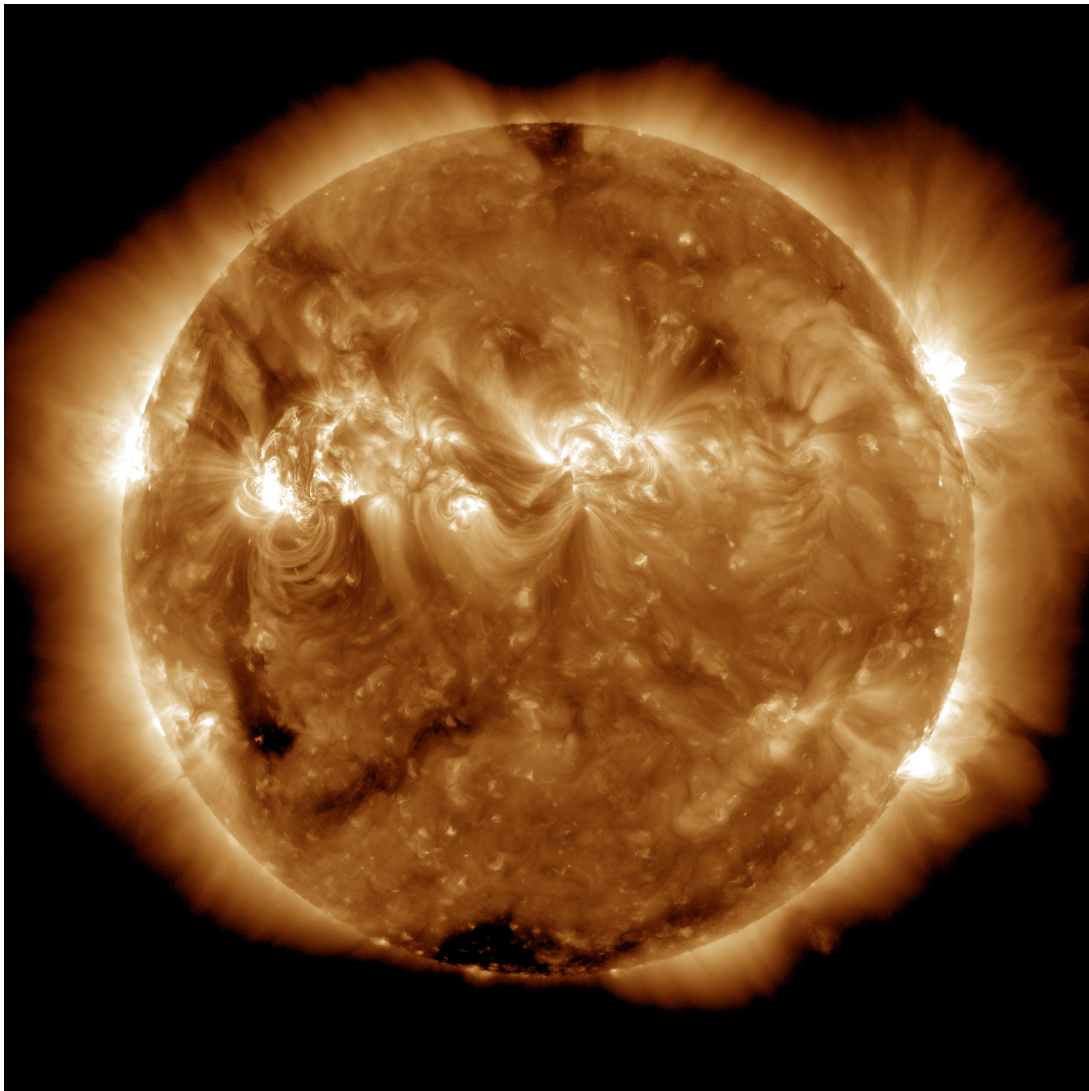


Figure 1.7: Solar image taken in the EUV band at $193 \text{ \AA}$ on the September 25, 2011 by Solar Dynamics Observatory (SDO)/Atmospheric Imaging Assembly (AIA). Credits: NASA/JSOC <http://jsoc.stanford.edu/>.

explains their darker appearance on the EUV image. On the contrary, ARs have high temperature and electron density and appear the brightest in EUV emission. They correspond to the bright features on the EUV context image, located at intermediate latitudes in both hemispheres. These regions are the source of large eruptions, called solar flares and Coronal Mass Ejection (CME)s. The third category, the QS, is in the middle range between the two other categories. The EUV context image presents large areas of intermediate intensities, that is, the QS. The terminology can be misleading, as the QS is, in reality, highly active. Indeed, the QS is filled with small-scale loop systems, known as coronal bright points [Madjarska, 2019] that produce numerous eruptive events [Shibata et al., 1992; Raouafi et al., 2016]. The main difference with AR is that the scales are smaller in the QS, as seen in the numerous small brightenings in Figure 1.7.

Now that the solar context is set, let us dive into the connection between the source region and the type of solar wind. The Ulysses mission revealed the link between coronal structures and the velocity of the solar wind. Figure 1.8 shows the solar wind velocity during three orbits of Ulysses [Balogh et al., 1999], with an EUV image in the background to allow for comparison. The left panel shows that, at solar minimum, fast solar wind originates from high-latitude regions in the CHs. In contrast, a slower wind is observed at lower latitudes, correlated with coronal streamers. The streamers are hotter, denser, and brighter than other coronal regions. They have a cusp-like shape and connect regions of the Sun with different polarities, as illustrated in Figure 1.6.

Ulysses was a solar mission that aimed to study the Sun at different latitudes, contrary to previous missions that stayed in the Earth's ecliptic plane. A gravity assist was performed, using Jupiter as an ideal planet to launch a spacecraft out of the ecliptic. It was then on a path to orbit around the North and South poles of the Sun. Interestingly, this mission provided striking measurements that allowed for a new consideration of the solar wind and its origin. The three orbits covered part of the solar cycle, with more than 11 years to observe a solar minimum and a solar maximum with the same instruments. The first orbit showed the latitudinal variations of the wind velocity. What becomes interesting about this apparent duality of slow and fast wind related to coronal structures is that it depends on the solar cycle. The picture I described previously prevails at solar minimum, whereas it becomes more complex at solar maximum. This complexity is observed in the middle panel of Figure 1.8. At solar maximum, slow and fast winds are not separated easily with the latitude and appear to emanate for all latitudes. As the Sun is at its maximum activity, the solar surface shows more ARs. That reveals the complexity of the origin of the solar wind, especially the slow solar wind, which is not always collocated with streamers.

Several challenges still have to be overcome to solve the slow solar wind origin. First, as the corona is structured by the magnetic field, it is necessary to understand the magnetic processes occurring in this region. What is challenging about the coronal magnetic field is that there are no direct observations of the magnetic field, because the magnetic field is too weak to be retrieved as it is for the photospheric field. The information we obtain about the field lines is due to the plasma trapped or frozen

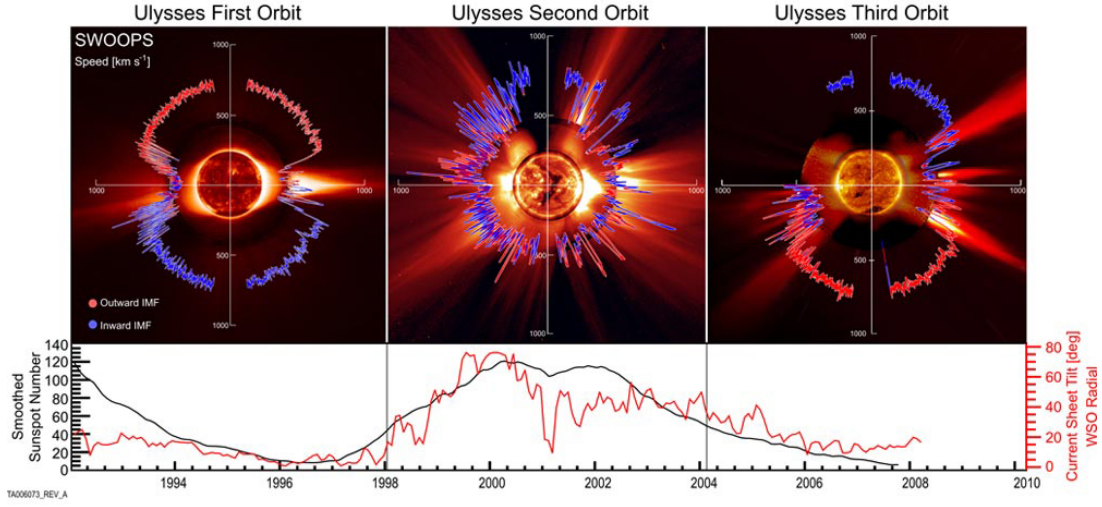


Figure 1.8: Evolution of the solar wind speed at solar minimum and maximum. Reproduced from [McComas et al. \[2008\]](#).

along the magnetic field lines, as mentioned above. Then, as they are observable with specific instruments, with intensity varying with the square of the electron density, we can probe the structure of the magnetic field. A second challenge is that the plasma is not as dense in the corona as it is close to the surface, as observed in Figure 1.3, so it is difficult to detect most of the plasma structures and, thus, field lines at larger distances. To overcome those difficulties, coronagraphs were sent to space, with an occulting disk covering the solar disk. That allows direct remote images of the coronal structures. This can also be done on rare occasions from the Earth's ground during total solar eclipses. One can compare the maximum and minimum stages of the solar cycle as in Figure 1.9. To allow for direct comparison, the full circle image is unwrapped and mapped into polar coordinates, so the limb is, in fact, the middle line. The top panel shows the structure of the solar corona taken during a solar maximum eclipse, while the bottom panel shows the corona during a solar minimal eclipse. One can observe the apparent simplicity of the corona during the solar minimum with the equatorial streamers and the coronal holes at the poles. On the contrary, the solar maximum shows numerous complex structures and more high-latitude streamers.

1.1.4 Solar wind release

The question of the source regions is only the first step on the path towards understanding the formation of the solar wind. The next step is to consider the phenomena that can release the solar wind. Three phenomena are generally considered: open fields, interchange reconnection, and closed-flux reconnection. The release mechanisms that are investigated are studied for their ability to produce changes in the magnetic field

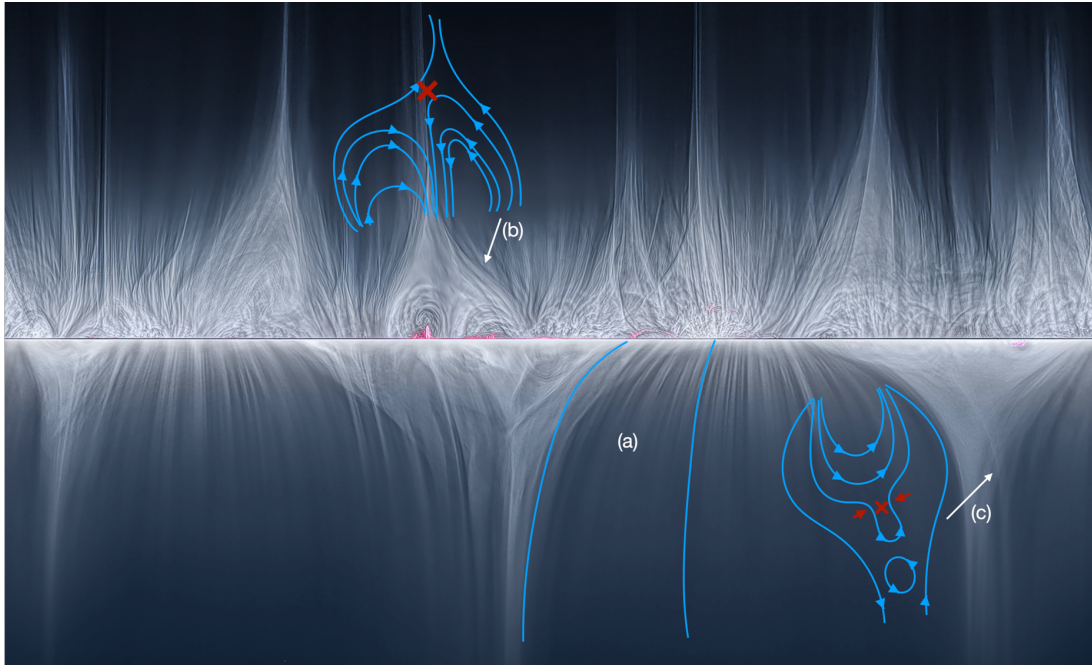


Figure 1.9: Composite images taken during two total solar eclipses, with a mapping in polar coordinates. The full circle image is unwrapped to get the limb as the line in the middle. The top panel is from the 2023 solar eclipse, and the bottom panel is from the 2017 solar eclipse. The two eclipses occurred during different stages of the solar cycle, with the 2017 eclipse close to the minimum and the 2023 one closer to the solar maximum. The figure also presents a schematic of the three possible mechanisms that can release the solar wind: Open field configuration (a), interchange reconnection in (b) and pinch-off reconnection in (c). Adapted from Peter Ward eclipse image (Barden Ridge Observatory).

topology and plasma properties that are schematized in Figure 1.6 [Viall and Borovsky, 2020; Cranmer et al., 2017]. I will now detail each of them, illustrated by the schematic overlapping in Figure 1.9, which reveals the release mechanisms in the context of a solar eclipse.

The first possibility is that the field lines are open to the interplanetary space, as observed in schematic (a) in Figure 1.9, so the plasma is released through open flux. That would require the field to remain open for longer timescales, which is the time the plasma takes to accelerate in the corona. The distinction between fast and slow wind could then be the result of different expansion factors. In the open flux context, flux tubes in the orientation of the magnetic field would have an expansion factor anticorrelated with the wind speed [Wang and Sheeley, 1990]. In a certain configuration, if the magnetic field diverges rapidly with heights, the energy would be deposited in the low corona [Wang et al., 2009]. That energy would be directly related to the local magnitude of the field, which is smaller at the boundary of CHs than in their cores. The boundaries of CHs are then considered to be a probable source of the slow solar wind.

A second possibility is based on magnetic reconnection between open and closed field lines, called interchange reconnection [Crooker et al., 2002], as observed in the schematic (b) in Figure 1.9. Magnetic reconnection refers to the breaking and reconnecting of oppositely directed magnetic field lines that change the local topology of the field. In the specific context of interchange reconnection, an open field line would reconnect with a closed loop, which leads to a new open field line, located at the footpoint of the original loop. The new loop system is then formed with the initial open field line and the second loop footpoint. Interchange reconnection can occur at the boundaries of CHs, where the open field is surrounded by closed field lines. Interchange reconnection can also appear in structures with complex topology, the pseudo-streamers [Titov et al., 2012]. Their shape is similar to the streamers that I discussed before, but they differ by the unipolar magnetic field in which they are embedded. These pseudo-streamers are also investigated for their possible link with the slow solar wind [Pellegrin-Frachon et al., 2023]. On smaller scales, interchange reconnection events occur in small-scale loops present in the QS, the coronal bright points, but is not limited to the presence of coronal bright points as it can occur at any open-closed field boundary, with the presence of null points. The interchange reconnection events are shaped as eruptive events, ejecting collimated flows, i.e. jets, that are omnipresent in the lower corona. The interest in these small-scale eruptive events is that, as for larger scale structures, they can allow mass and energy to be injected into the solar wind [Raouafi et al., 2016].

Reconnection can also occur in closed-field configurations, such as the top of the streamers, and is then referred to as pinch-off reconnection [Higginson and Lynch, 2018], as observed in the schematic (c) in Figure 1.9. This type of reconnection produces plasma that is disconnected from the Sun. The reconnection event can produce flux ropes at the top of the streamer that could then account for the variability observed in the slow solar wind [Viall and Vourlidas, 2015]. However, these events are usually observed at equatorial latitudes. This would not explain the observation of slow winds

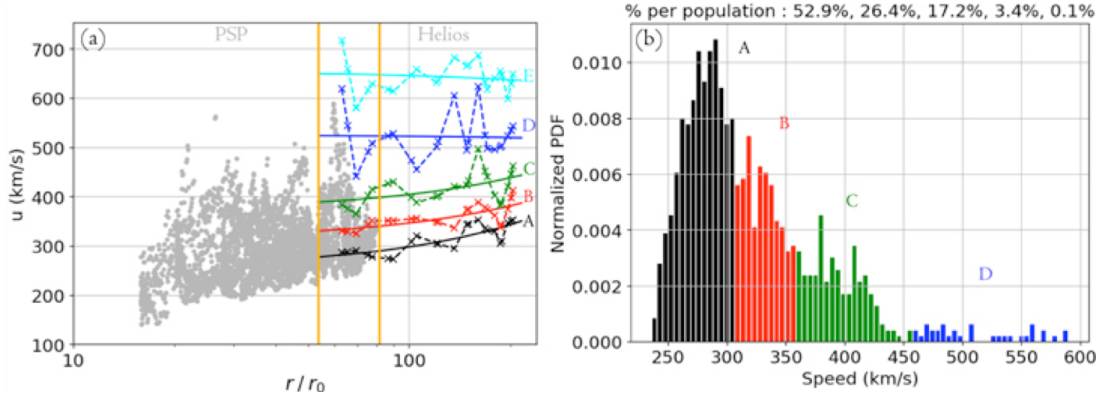


Figure 1.10: Solar wind (proton) velocity measurements from Helios and Parker Solar Probe (PSP) plotted as a function of the radial distance to the Sun. Reproduced from [Dakeyo et al. \[2022\]](#).

at higher latitudes.

The complexity of resolving the solar wind release question is due to the small scales at which reconnection occurs that they have not yet been resolved in the solar corona with remote sensing instruments.

1.1.5 Solar wind acceleration

At this stage, the solar wind, originating from a certain region, is formed and expelled out of the solar corona. The Parker solution I presented previously theorizes that the heated corona produces a supersonic solar wind [[Parker, 1958](#)]. Thus, the solar wind is accelerated due to the high-temperature corona. Both open questions are then related, and the acceleration of the solar wind answer may reside in the phenomena responsible for the coronal heating. The wind continues to accelerate as the plasma travels in the interplanetary space to reach super-Alfvénic speeds. This is observed in the proton bulk speed measured by space missions (see Figure 1.10). Interestingly, the limitations of the duality of the solar wind velocity are then highlighted. The slow solar wind category shows sub-populations of wind with different slopes, and thus different acceleration profiles [[Dakeyo et al., 2022](#)].

The acceleration of the solar wind requires an additional energy deposition through certain mechanisms: closed-flux reconnection, interchange reconnection, component reconnection, and waves. Reconnection events could bring energy to the solar wind, but the exact amount of energy brought by reconnection to accelerate the solar wind is still unknown. These events would be different from the events that allowed the solar wind to be released [[Viall and Borovsky, 2020](#)]. Component reconnection has not been investigated as a possible mechanism that can release plasma because it occurs between two open field lines. However, this reconnection, observed in the open fields of CHs [[Tenerani et al., 2016](#)], can however accelerate the solar wind. Other promising phenomena are Alfvén waves, which would be produced in the solar atmosphere and

propagate along an open magnetic field [Cranmer et al., 2015]. The wave would deposit energy, and depending on the sonic transition point, it will be converted into heat or flow energy. That theory would be associated with the expansion factor theory introduced previously. The Alfvén waves appear to accelerate the fast solar wind that escapes through open field lines in CHs, as they provide significant momentum [Ofman, 2010]. In contrast, the thermal pressure alone is sufficient to accelerate the slow solar wind to the observed velocities, as shown by Parker [1958]. The possible influence of Magnetohydrodynamics (MHD) waves in the acceleration of the slow solar wind is still not resolved. Alfvén waves could also be launched at higher altitudes through small-scale interchange reconnection/eruptive events [Raouafi et al., 2016].

Although the measurements show clear acceleration profiles, it is highly difficult to develop good models that would fit the observations. A correct acceleration profiles would be of interest for space weather predictions, for example and I will further discuss this in Chapter 3, as I will require estimation of the solar wind velocity profile. The main issue with the determination of the solar wind acceleration models is to obtain reliable measurements of the wind velocity in the region in which most of the acceleration is carried out, in the low corona between 1 and 10 $R_{\odot}$ [Bemporad, 2017]. In fact, in situ measurements inside the lower corona are still not possible although spacecrafts that probe the solar wind as closely as possible may help determine the mechanisms at stake.

1.2 Magnetic switchbacks

1.2.1 Switchbacks first measurements

I first introduced the current context of solar wind physics. The numerous questions that remain unanswered led to the development of spacecraft missions to orbit the Sun. As I discussed previously, a great improvement could be made by sending a probe to close distances to the Sun, where the mechanisms that heat and accelerate the wind may just have occurred. That is one of the reasons that led National Aeronautics and Space Administration (NASA) to send a spacecraft, Parker Solar Probe (PSP), to be the closest spacecraft mission to the Sun [Fox et al., 2016]. It was launched in August 2018 by NASA. Its nominal duration is seven years, which will possibly be extended. The minimum distance to the Sun will be reached by the end of 2024. In December this year, PSP will be as close as 9.85 solar radii to the Sun center.

PSP has three main science goals. It aims to determine the structure and dynamics of the Sun’s coronal magnetic field, improve our understanding of the solar corona and solar wind heating and acceleration, and establish the processes that accelerate energetic particles. Different instrument suites compose the payload on board PSP, presented in Figure 1.11, that aim to bring new measurements to reach the scientific goals. The instruments used in my studies are the FIELDS suite [Bale et al., 2016], which measures the electric and magnetic fields of the solar wind and the Solar Wind Electrons Alphas and Protons (SWEAP) suite [Kasper et al., 2016], which measures

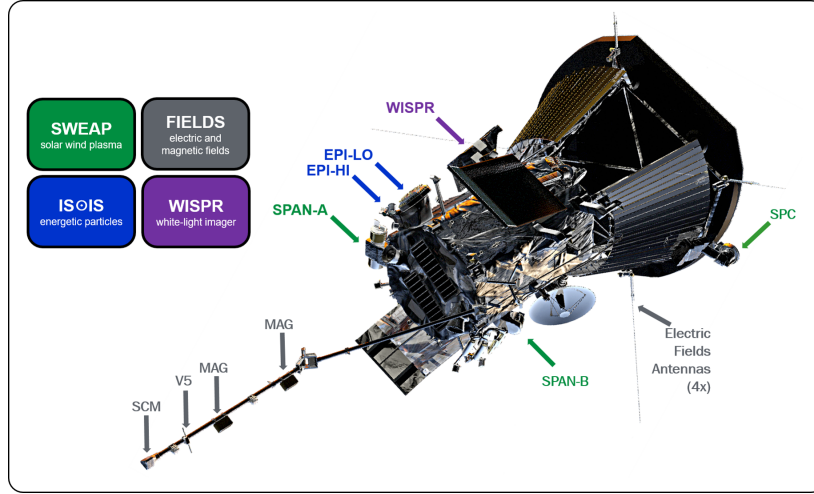


Figure 1.11: Payload on board PSP. Reproduced from sweap.cfa.harvard.edu.

the solar wind plasma. FIELDS is an instrument suite that is composed of various instruments: two triaxial flux-gate magnetometers MAG, a search-coil magnetometer Search Coil Magnetometer (SCM) [Jannet et al., 2021], both of them mounted on the boom, and five electric field antennas. Four antennas are almost in the plane of the spacecraft’s heat shield, while the fifth one is located on the boom. The heat shield is the thermal protection that allows to shadow the spacecraft instruments and provide 30°C while the outside face temperatures up to 1400°C . It is composed of a carbon-carbon composite/carbon foam sandwich [Fox et al., 2016]. The difference between the two types of magnetometers is the frequency range of fluctuations they cover. The MAG instruments measure the low-frequency range, from DC to approximately 100 Hz. The SCM instrument measures higher frequency, from 3 Hz to 50 kHz in one band. One of the antennae of the instrument allows it to cover a larger band, from 10 kHz to 1 MHz. A detailed description of the MAG instrument will be given in the next chapter. The other instruments of the two suites were not used for my study and are not included here. PSP carries two additional instrument suites, which are not relevant to this thesis and thus, will not be detailed in this discussion. A white light imager [WISPR, Vourlidis et al., 2016] is located on the side of the spacecraft so that it images the solar wind, and a second instrument suite measures solar energetic particles [IS⊙IS, McComas et al., 2016].

The first solar encounter of PSP revealed in the inner heliosphere a highly structured solar wind with the puzzling presence of sudden discontinuities. Figure 1.12 presents the magnetic fluctuations in the radial direction measured by PSP during its first encounter with the Sun (E01). From the previous in situ measurements and the theory of the solar wind, it was expected to observe small fluctuations, compared to the magnitude of the field, with a bulk direction centered around the radial Parker spiral. That ideal solar wind is illustrated by the constant black line in the figure. In that case, the polarity of the field is negative. The magnitude is proportional to the squared distance

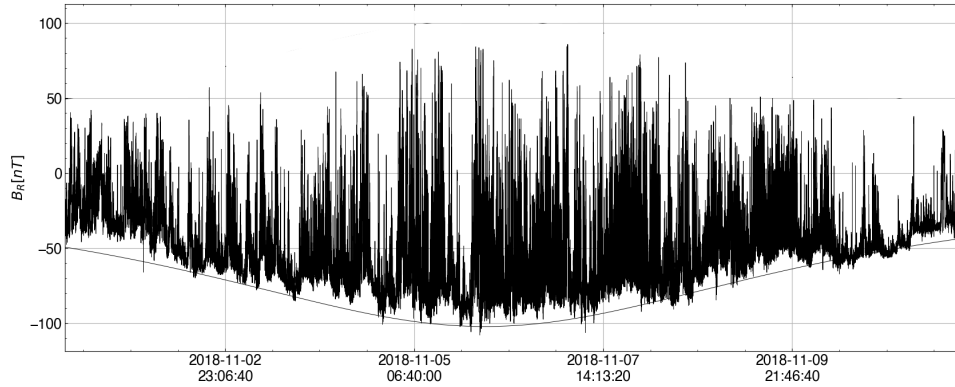


Figure 1.12: Magnetic fluctuations in the radial direction measured by PSP during its first encounter with the Sun. The constant line corresponds to the expected evolution of the magnitude of the field with the $1/r^2$ law. The perihelion is located around the maximum magnitude on November 06, 2018, at 03:27.

to the Sun, which explains the shape, with a larger magnitude close to the Sun. What was unexpected to be seen in this figure is the amount of large deflections, of the order of the field magnitude, that can lead to a complete reversal of the field. They are omnipresent in the measurements of PSP [Bale et al., 2019; Kasper et al., 2019].

Although PSP shows the omnipresence of these deflections that led to their extensive studies, it is not the first mission to observe the magnetic deflections that are the main subject of this thesis. The first observations of abrupt changes in the magnetic field direction were reported in in situ measurements from Mariner 2 [McCracken and Ness, 1966]. These deflections were interpreted as filament structures in the interplanetary magnetic field. Figure 1.13 shows the measurements of the magnetic field direction, with abrupt reversals. The cartoon on the right is similar to those that have been produced in recent years for the interpretation of the PSP data.

Horbury et al. [2018] likewise has revealed the existence of sharp velocity spikes observed by Helios when it was close to the Sun (0.29 au). These velocity increases, on a short timescale, are not observed at 1 au. They are correlated with magnetic fluctuations and have sharp boundaries and constant magnitude of the field. In contrast, a visible reversal of the field is observed in the radial direction, as presented in Figure 1.14. It is interesting to note here that they were first detected from measurements in the velocity field and not as reversals in the magnetic field. The complexity of the interpretation arises from the limited time resolution of the plasma measurements, highly limiting the number of events investigated. Magnetic reversals are also observed in Ulysses measurements at more than 1 au [Balogh et al., 1999].

The first mention of the term “switchback” is found in Yamauchi et al. [2004], to describe magnetic reversals that appear to fold back on themselves. That is one of the questions that should directly arise when such conclusions are based on single-point measurements. Indeed, the time-series from a single spacecraft alone cannot provide a

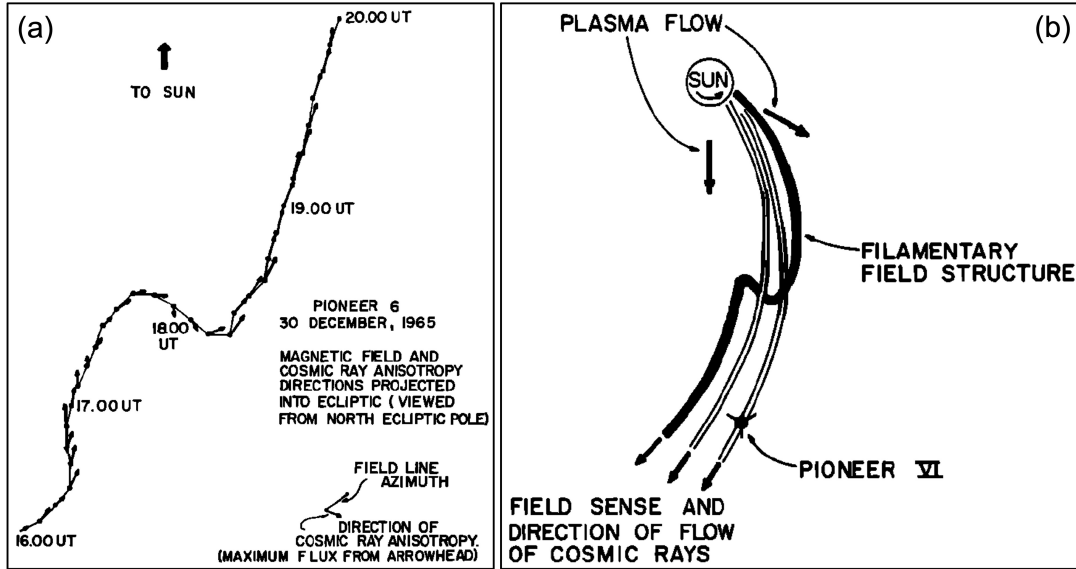


Figure 1.13: Abrupt changes in the magnetic field direction observed by Mariner 2. These were theorized as interplanetary filament structures. Reproduced from [McCracken and Ness \[1966\]](#).

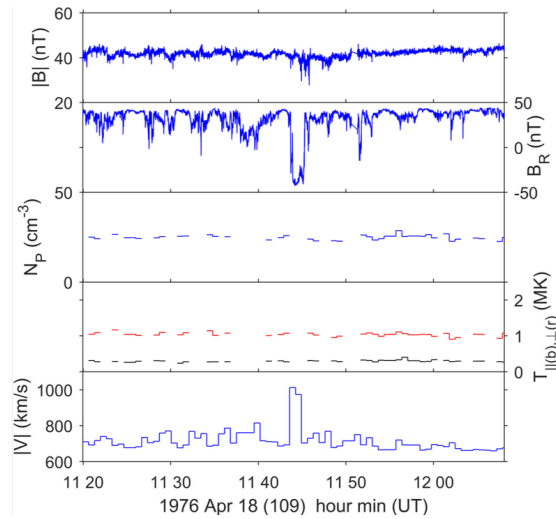


Figure 1.14: Velocity spike observed by Helios 2 at 0.29 au in 1976. It is associated with a magnetic field reversal in the radial direction. Reproduced from [Horbury et al. \[2018\]](#).

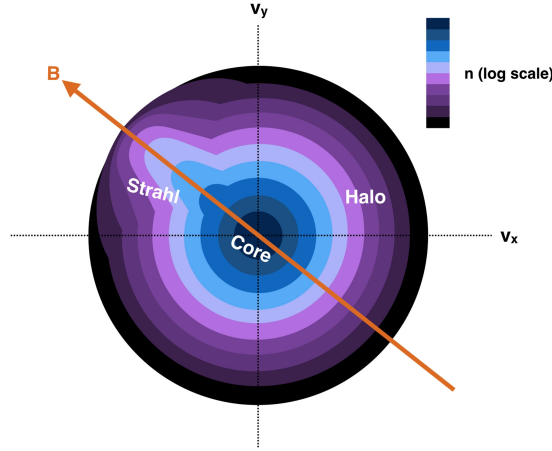


Figure 1.15: Schematic view of the electron velocity distribution. It shows the three subgroups: core, halo, and strahl. Reproduced from [Graham et al. \[2017\]](#).

full 3D understanding of the structure. A similar magnetic signature could be observed if the spacecraft is crossing multiple field lines with opposite polarity. This question can be addressed through the population of energetic electrons called strahl electrons.

1.2.2 A topology indication through strahl electrons

The velocity distribution function of the electrons is composed of 3 sub-populations: the core, the halo, and the strahl electrons, illustrated in Figure 1.15. Here, we are interested in the high-energy electrons. The strahl consists of suprathermal electrons with high energies that form a beam that follows the magnetic field lines and always propagates in the anti-sunward direction [[Feldman et al., 1975](#)]. This property is then a tracer of the magnetic field topology, indicating the connectivity to the solar surface. This can be considered as a near-instantaneous topology indication, as the strahl electrons travel faster than the bulk plasma flow. The pitch angle of the electrons is a parameter that allows us to probe the angle between the particle velocity vector and the ambient magnetic field vector.

Four different configurations are presented in Figure 1.16. The simple cases are shown in (a) and (c) when there is a single connection with the surface, representing the open magnetic flux. Thus, a single population of strahl electrons is observed. Then, the parallel or antiparallel strahl represents the polarity of the footpoint. At (a), the polarity is inward, so the strahl is antiparallel. We see the opposite case with parallel strahl at (c). A second configuration is observed at (b), with a closed loop connected on both sides to the surface. Thus, two populations of strahl are observed, as the loop presents two polarities while the strahl propagates outward. The last case is when the field line is not connected to the solar surface, so no strahl is observed, as seen in (d).

If one tries to connect the theoretical configurations presented above with the measurements of the magnetic field direction, we could imagine that the spacecraft crosses

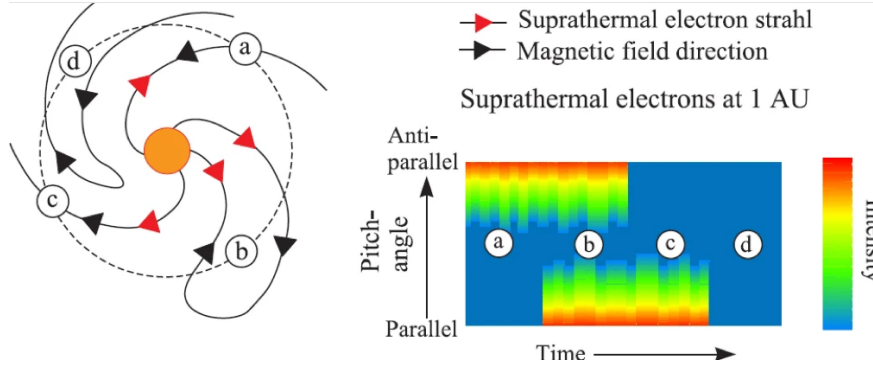


Figure 1.16: A schematic representation of the magnetic topology that can be inferred by the strahl electrons. Left panel: View of the ecliptic plane, with the magnetic field direction represented by the black arrows and the strahl electron flux by the red arrows. Right panel: Strahl electron pitch angle as seen by an in situ probe for the different field line configurations. An antiparallel strahl in (a) is the result of the inward polarity of the field line. The opposite polarity of configuration (c) shows a parallel strahl. A closed loop with both sides connected to the surface, as (b), results in both parallel and antiparallel strahl. No strahl is observed for the line without solar connection, showed in (d). Reproduced from Owens and Forsyth [2013].

a succession of field lines with different polarities. That would be observed in the time-series in the case of an Heliospheric Current Sheet (HCS) crossing. One would successively observe a pitch angle measured as (a), then (c), and back to (a) as the polarity changes between the lines. However, the pitch angle of the strahl electrons does not change during the crossing of the structures, observed by PSP, revealing that these are not HCS crossings. As the pitch angle does not change but the apparent polarity changes, it can only correspond to bendings of the magnetic field away from the Parker spiral and sometimes back to the Sun [Kasper et al., 2019; Whittlesey et al., 2020].

1.2.3 Current definition of a switchback

A switchback is defined as a sharp deflection of the magnetic field vector away from the ambient direction and back. The sharpness refers to the short boundaries compared to the duration of the deflection. Switchbacks are now known to be self-similar [Dudok de Wit et al., 2020; Bizien et al., 2023]. That implies that there is no characteristic deflection angle. Although there is no definite threshold for the minimal angle of deflection to be considered a switchback, it should at least be higher than the local level of fluctuations. That corresponds to a few tens of degrees. Most switchbacks present small deflections of less than 90° . However, some are full reversals of the magnetic field, which gave the name to these structures. Ongoing simulations of these deflections aim to reach an inversion of the polarity, with a deflection angle above 90° in order to understand their formation and evolution. Lower deflection angles are

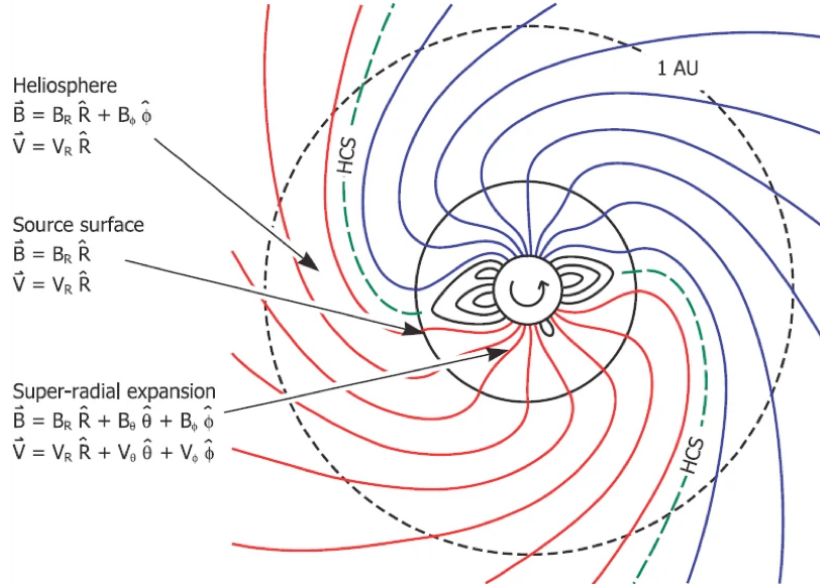


Figure 1.17: Schematic view of the solar ecliptic plane steady-state magnetic field. Reproduced from Owens and Forsyth [2013].

more easily produced in these simulations, but it becomes highly challenging to reach a complete reversal.

1.2.4 Deflections from the background field: the Parker spiral

As I discuss deflections of the magnetic field, it is necessary to define a reference to which it is deflecting. The natural reference is the Parker spiral, which can be defined as follows. We first assume a steady-state ideal solar wind with a purely radial wind at constant speed. We assume no dependence on the radial or latitudinal position. We consider idealized field lines with footpoints anchored in the photosphere, and thus we only consider the solar rotation. The magnetic field is frozen in the coronal plasma and is thus carried out into the interplanetary space by the solar wind. As the plasma β is greater than 1, beyond the sonic point, the solar rotation forces the field lines to become twisted in the form of an Archimedean spiral, observed in the equatorial plane. This spiral, illustrated in Figure 1.17, was predicted by Parker [1958], and is usually called the Parker spiral. For my studies, I estimate the Parker spiral from the solar wind measurements, with the methodology I will present in the next Chapter.

1.3 Switchback properties

In this section, I discuss the main properties of the switchbacks that have been discovered and discussed so far. It does not mean to be exhaustive but is intended to provide the reader with a global understanding of the switchbacks.

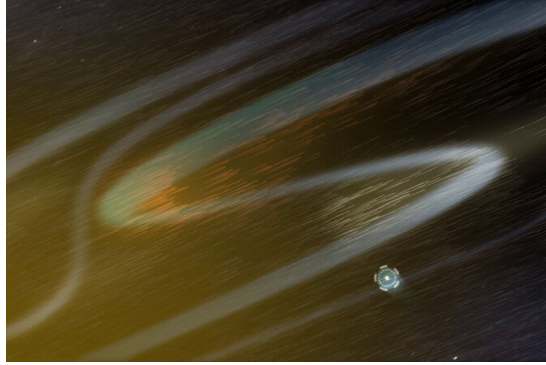


Figure 1.18: Frame from a [NASA](#) animation showing the crossing of a switchback by a probe. This is an assumption, as it just shows a simple picture of the complex structures. Credit: NASA/GSFC/CIL/Adriana Manrique Gutierrez

1.3.1 Geometry

A complete understanding of the 3D geometry of the switchbacks is difficult, as we are limited by the single-point measurements of [PSP](#). In fact, we can only cross the structure at one specific location. That allows us to discuss the reversal, but the full picture seems to be out of reach. However, many cartoons have been proposed to explain the possible 3D structure of switchbacks. Most of them only show a 2D representation of the structure and miss the full picture (see Figure 1.18). These are also limited. For instance, a single field line can undergo multiple reversals. As we measure switchbacks at all distances, one could imagine a field line or a bundle of field lines reversing at multiple solar distances. Moreover, the simplest images of S-shaped structures presented in many publications as well as for the public are therefore misleading. Another challenge in understanding the geometry of the structures is in the variety of characteristics observed, from their different deflection angles and duration to the numerous substructures embedded in the switchbacks. A cartoon that may be closer to reality is presented in Figure 1.19. Indeed, here, the field lines show different deflection angles, with multiple deflections on the same field line.

If we move into the closer picture, focusing on a single switchback, it appears as an elongated structure, as illustrated in Figure 1.20. [Horbury et al. \[2020\]](#) determine the structures to be long and thin, with a high aspect ratio in the radial direction. The structures are tens of thousands of kilometers across. In situ measurements are highly dependent on the crossing of the structure by the spacecraft. In fact, if one considers the elongated structures presented in Figure 1.20, the signature in the time-series would differ for the two cases presented. In fact, an apparent long-duration crossing of the structure may indicate a crossing almost parallel to the radial direction, as in panel B. In that case, one could overestimate the size of the structure. The orientation of the switchback related to the radial direction should then be estimated. Thus, it was necessary to determine the velocity through which the spacecraft crosses the structure [[Horbury et al., 2020](#)]. For a larger set of switchbacks from different encounters, [Laker](#)



Figure 1.19: Artistic impression of the switchbacks in the solar wind. Credit: NASA/Johns Hopkins APL/Ben Smith

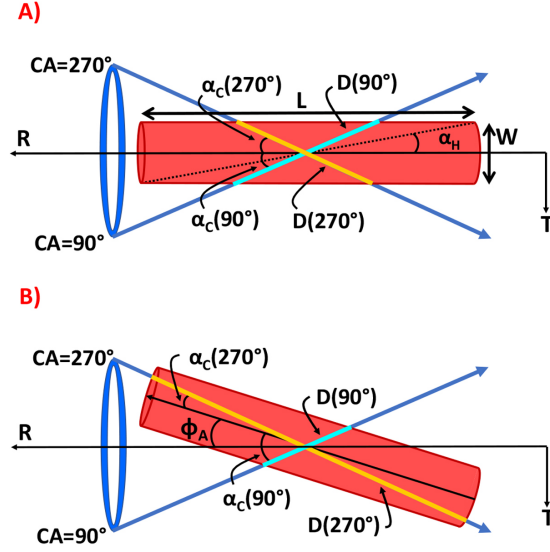


Figure 1.20: Illustration of the influence of the crossing of the switchback on the apparent duration in the time-series. Two magnetic configurations are shown, with a switchback aligned with the radial direction and a second with a tilt from the radial direction. The probe trajectory is represented by the blue arrow. Two different trajectories are presented for each case. Then, for each case, the crossing section of the structure is highlighted in orange. For case A, the crossing angle of the spacecraft does not influence the duration in the time-series. Case B shows the influence of the crossing angle, with a longer duration, if the crossing occurs along the main dimension of the switchback. Reproduced from [Laker et al. \[2021\]](#).

[et al. \[2021\]](#) estimated the width to be approximately of 50 000 km and an aspect ratio of the order of 10.

Moreover, switchbacks appear to have a preferential orientation in the clockwise tangential direction with respect to the Parker spiral [[Fargette et al., 2022](#); [Laker et al., 2022](#)]. That is theorized to be a possible link with their solar origin.

1.3.2 Switchbacks: Alfvénic structures

The correlation of fluctuations of the magnetic field with positive velocity spikes observed in the solar wind is a signature of Alfvénic structures propagating in the solar wind in the anti-sunward direction [[Matteini et al., 2014](#)]. Switchbacks are similar to Alfvén waves because their magnetic intensity is nearly constant across their boundary. In addition, changes in magnetic field and velocity field are correlated [[Kasper et al., 2019](#)], as observed in Figure 1.21. However, they are not purely Alfvénic, as they are also weakly compressible, and dropouts of $|\mathbf{B}|$ have been observed at their boundary [[Farrell et al., 2020](#); [Larosa et al., 2021](#)]. For that reason, they are sometimes referred to as near Alfvénic. Moreover, some velocity spikes are associated with an increase in the proton density, which is a signature of a non-Alfvénic component [[Kasper et al.,](#)

2019].

This property is crucial for the first work that I will present in Chapter 2. Indeed, the magnetic field direction changes during the crossing of the switchback and, more particularly, during the crossing of its boundaries. The deflection is constrained by the Alfvénicity, as the field magnitude is constant. That forces the tip of the field vector to rotate on the surface of a sphere. That geometric property will show its importance in the analysis of the boundaries which, in turn, are one of the keys towards understanding the origin of the switchbacks.

1.3.3 Switchback patches

Individual switchback properties show complexity that is not yet completely resolved. However, they appear to have a global behavior. Indeed, switchbacks tend to appear in patches. The patches are the intervals in which we observe several large deflections that could last several hours. They have a size scale about the same order as the solar supergranulation scale [Bale et al., 2021; Fargette et al., 2021].

However, we should be clear about the patches and their meaning. If we consider the number of large deflections, we see an apparent regular fluctuation with many deflections and quieter intervals with very few deflections. In contrast, if one considers all the deflections above the noise level, the number of switchbacks is almost constant. Thus, the modulation is not about the number of switchbacks but about the magnitude of the deflection [Dudok De Wit et al., 2024].

The switchback patches observed in the time-series are also due to temporal variations. In fact, during the corotating interval of Encounters 01 and 10, Shi et al. [2022] showed a temporal scale that cannot result from a link to the supergranulation. During corotating intervals, the footpoints of the magnetic field lines on the Sun move by only a few Carrington degrees at most. For example, during the relatively long interval of 42 h of the corotation of E10, the footpoint only moves about 3.5° in longitude. The supergranular cell sizes range from 1.6° to 6.2° at source surface [Fargette et al., 2021]. Their typical lifetime is about 41 h [Rincon and Rieutord, 2018]. In that situation, the observation of multiple patches should be linked to temporal fluctuations and not to the crossing of solar wind from multiple supergranular cells.

1.3.4 Switchback occurrence

The switchbacks are outstanding for their high occurrence rate in the PSP observations. However, the study of the evolution of occurrence rate could bring more understanding to these large reversals, with hints of their origin. A comparison of occurrence analyses is problematic, as the lower value of the angle of deflection included in the studies may vary. The studies may also include different parameters to count the structures (minimal deflection angle, correlated velocity, an identified source region, etc.) or to be used as a reference (the background field or the Parker spiral). Mozer et al. [2021a] shows that a large deflection (over 90°) occurrence rate is not dependent on the radial distance. However, these conclusions are based on hourly averaged numbers,

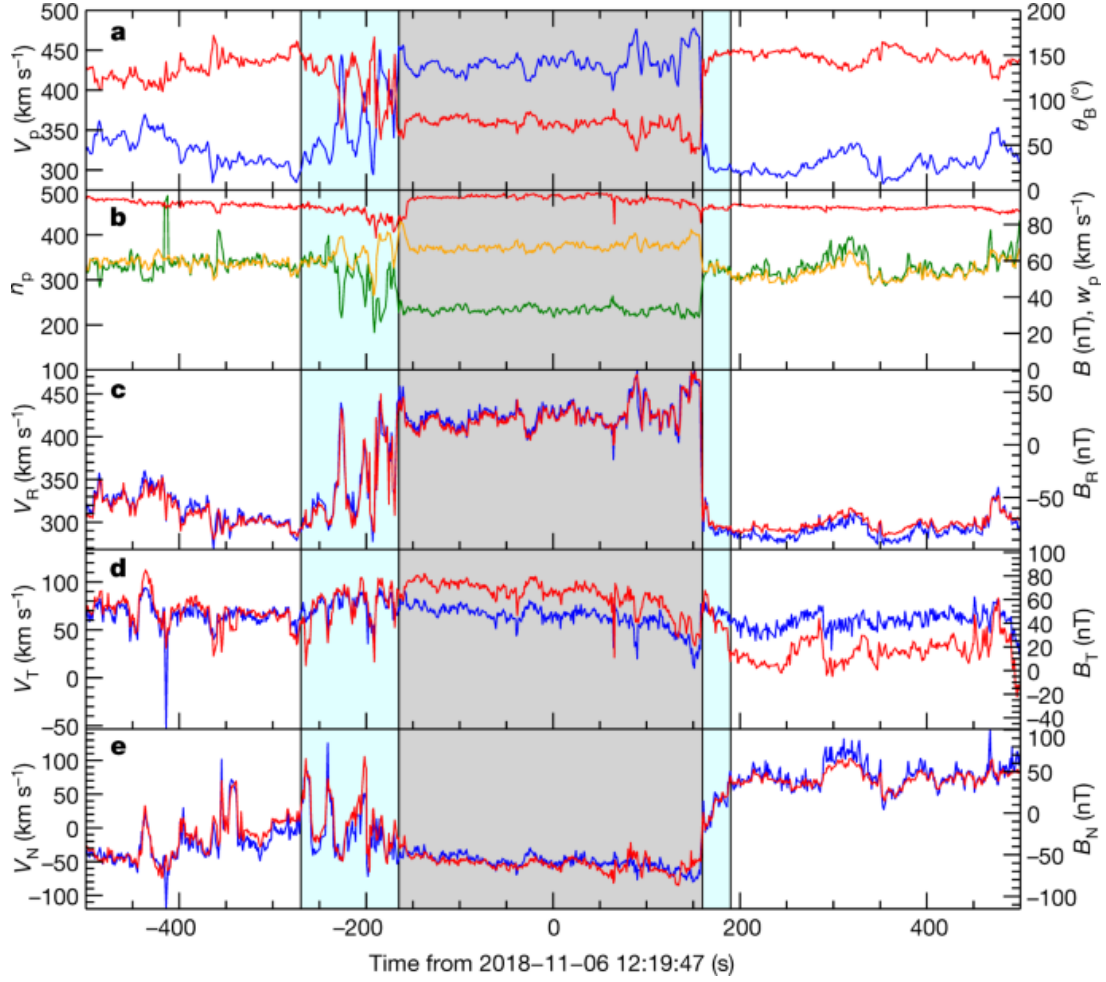


Figure 1.21: Solar wind parameters measured during the first encounter of PSP, with a typical switchback (interval in gray). The magnetic reversals are associated with positive velocity spikes, as shown on panel a. The velocity jets are about 100 km s^{-1} above the bulk solar wind velocity. The last three panels show the correlated velocity and magnetic field fluctuations in the three components. Reproduced from [Kasper et al. \[2019\]](#).

which do not take into account the type of wind and, more particularly, the different velocities. Normalization then greatly impacts the results and should be done carefully when interpreting the occurrence rate. Normalization could be performed with respect to the solar wind velocity as well as the time spent at a certain distance from the Sun by the spacecraft during its numerous orbits [Jagarlamudi et al. \[2023\]](#) shows that the number of large deflections increases with the distance to the Sun, whereas the number of smaller deflections decreases. They also found a connection between the solar wind velocity and the occurrence rate of switchback. When the wind is faster, they observe more switchbacks. [Tenerani et al. \[2021\]](#) shows that the occurrence rate is scale-dependent, and the probability of finding longer-duration switchbacks increases with the radial distance, while it decreases for shorter-duration switchbacks. [Pecora et al. \[2022\]](#) shows that the occurrence rate varies with the distance to the Sun, with a clear difference inside the Alfvén critical zone, where it is lower. This zone refers to the region in which the Alfvén speed is much higher than the wind speed. Outside this zone, the solar wind is strongly super-Alfvénic, with a speed that exceeds the Alfvén speed.

The issues with such studies are the definition of a proper rate of switchbacks under different conditions. In fact, one could focus on the background wind properties to classify switchbacks and then compare the occurrence rate. In theory, the evolution of the occurrence rate with the radial distance can be used to estimate the origin of the switchbacks. As one would observe an increasing number of deflections as the distance to the Sun increases, it could mean that some in situ generation processes are required to increase this number. However, we consider single-point measurements at different stages of the orbit. Thus, it is risky to compare the numbers. Observing more switchbacks at a certain distance on a certain orbit would not mean that there is an increasing number of switchbacks as the spacecraft measures further away from the Sun. A tentative extrapolation of the trend observed in the occurrence back to the Sun could be implemented to find the start of the switchback generation. [Pecora et al. \[2022\]](#) found this distance to be around 20 solar radii. This would emphasize a generation in situ, with no switchbacks below that distance. However, switchbacks have been observed at distances closer than $20 R_{\odot}$, which contradicts this hypothesis.

All of these occurrence studies focused on the switchback rate. However, the distribution of angles also varies with distance. That gives more information on the possible in situ generation or the growth of small deflection with the solar wind expansion, for example. This is attempted in [Jagarlamudi et al. \[2023\]](#) and in [Dudok De Wit et al. \[2024\]](#). The difficulties in comparing both studies are directly related to the initial problem, that is, the proper definition of a switchback rate and the implemented normalization.

1.4 Switchback generation theories

While switchback omnipresence allows for extensive statistical studies of their in situ properties, one major unknown remains, namely their origin and formation mecha-

nisms. Several theories are proposed, but no agreement has yet been found. The first theories were debated after the first orbits, when PSP was still at large distances from the Sun, around $35 R_{\odot}$. Switchbacks are measured at distances as far as Earth's orbit so that we can, in theory, follow their evolution and propagation. However, we need measurements closer to their origin site to resolve their formation. Indeed, during their propagation, various processes could operate within the solar wind and hide the markers of their origin.

We can separate the formation theories into two categories. The first argues that switchbacks are structures formed in situ in the solar wind, depending on specific plasma conditions. The second category supports the origin of switchbacks as perturbations originating from the low solar atmosphere. These theories are mainly based on interchange reconnection, defined as the magnetic reconnection between closed and open fields [Crooker et al., 2002]. I present here a non-exhaustive list of theories that represent the most discussed phenomena that could be precursors of switchbacks.

First, let us discuss the in situ formation theories. Squire et al. [2020] developed the theory that switchbacks are the result of the evolution of Alfvén waves propagating in the solar wind. Their model simulates the expansion of Alfvénic fluctuations with the constraints of constant $|\mathbf{B}|$ and radial magnetic field. This results in similar features as observed by PSP, including the steepening of the waves to form strong discontinuities. The suggested explanation is based on large variations of $\delta B/B$, due to a faster decrease of the magnetic field compared to the fluctuations, which is balanced by a constant $|\mathbf{B}|$. Ruffolo et al. [2020] argued about the combination of shear flow and non-linear Kelvin Helmholtz instabilities to generate switchbacks locally in the solar wind. Firehose instabilities can also produce highly kinked field lines in the condition of high-beta plasma [Tenerani and Velli, 2018]. Indeed, in such conditions, simulations show that circularly polarized Alfvén waves would evolve to form magnetic field reversals. This theory is supported by observations in Krasnoselskikh et al. [2020], who theorized that reversals could be the result of this type of instability. Toth et al. [2023] proposed that switchbacks originate within Alfvénic turbulence due to the large-scale transverse shear in the radial wave velocity, consistent with findings from idealized simulations.

The second category argues for the generation of a perturbation in the low corona that directly produces a reversal or gives birth to seeds that would propagate and grow to become switchbacks. Fisk and Kasper [2020] developed the hypothesis of interchange reconnection between open and closed field lines that would generate the reversals of the field lines. Interestingly, this seems to be observed in the simulations of Zank et al. [2020]. However, this hypothesis is assuming that the magnetic tension would not straighten the field lines directly after they are deflected. In the basic setup described in the theory, it seems to be a significant assumption to allow the deflection to persist. The current modeling focuses on a certain level of complexity to act against the magnetic tension. Drake et al. [2021] theorized the origin of switchbacks with flux ropes emerging due to interchange reconnection. These flux ropes are the reversals observed in the solar wind. Coronal jets, which are the result of interchange reconnection, may also produce switchbacks [Sterling and Moore, 2020]. Schwadron and McComas [2021] stated that

the movements of the magnetic footpoints would generate interchange reconnection that creates a super Parker spiral arm. The combination of a super-Parker and sub-Parker spiral creates shear flows that then generate switchbacks. [Bale et al. \[2021\]](#) claimed that the interchange reconnection occurring above the funnels can produce switchback patches. Funnels are magnetic structures rooted in the photosphere with a narrow width that then expand in the corona [[Tu et al., 2005](#)].

Currently, no studies are able to prove that one theory is prevalent on the others. There is also no proof of a unique possibility. The conditions for creating a switchback can be divided into two stages. First, we should focus on the generation mechanisms that would allow a perturbation of the magnetic field produced in the solar corona or below to propagate away from the Sun without being immediately damped. The second aspect is directly related to the propagation of these perturbations. One hypothesis could be that the initial precursor event could grow and be amplified to reach the structure with the properties measured at [PSP](#).

The propagation stage highly impacts the possible conclusions on the origin. What should be investigated are the different properties at different heliospheric distances and if different populations can be identified. However, variations could be observed as the result of different solar origins of the streams and would not be an indicator of solar origin or in situ formation. If no variations are observed, it could also indicate that all switchbacks have a solar origin, but their properties and evolution were shaped below the closest distance observed by [PSP](#), such as below the Alfvénic radius. This would lead to a uniform population of switchbacks.

1.5 Evolution of switchbacks

1.5.1 Current limitations

To understand the evolution of switchbacks, one would need to follow the same transient event from its origin to its decay. However, with the added limitations of single-point measurements, we can only measure transient events at specific locations around the Sun. Coordination campaigns are attempted using the fleet of spacecraft probing the solar wind around the Sun [[Rivera et al., 2024b](#)]. Specific configurations may allow probing the same plasma parcel from [PSP](#) to Solar Orbiter and spacecraft. at the Earth's orbit. That is a challenge and is close to my objectives in the second investigation of this thesis, which I will present in Chapter 3.

1.5.2 Dissipation

Switchbacks seem to disappear and mix with the local solar wind. While it is still unclear about the trend of the evolution of the occurrence rate, as this is an observation highly dependent on the population of switchbacks studied, the occurrence rate appears to vary with the radial distance. Various mechanisms may play a role in the dissipation of some of the switchbacks. That is of interest because it may be directly related to the

heating and acceleration of the solar wind. Waves at the boundary of switchbacks could erode the structure and lead to their mixing with the solar wind [Krasnoselskikh et al., 2020]. Reconnection is also investigated, as it could change the local configuration of the magnetic field and erode the structure. Some cases have been reported in [Froment et al., 2021; Suen et al., 2023]. A discussion on the timescale at which these phenomena would erode the structures is necessary, as we still observe switchbacks at larger distances. Suen et al. [2023] reported the estimation of the timescales of switchback erosion, which are lower than the timescales and spatial scales of the expanding solar wind. It would suggest that reconnection is a fast mechanism that can erode switchbacks. Tenerani et al. [2021] suggested that the switchbacks observed at any time could be a mix of different structures, some that are remnant of solar origin phenomena that would slowly decay as they propagate, but the total number of switchbacks would stay relatively high with an in situ generation.

1.6 Motivation

I have now introduced the global context of the magnetic reversal structures observed by PSP in the solar wind. Although switchbacks are not unique in themselves, what explains the great attention paid to them since PSP has been operating is their ubiquity in the inner heliosphere and their possible connection to the mechanisms that could heat the corona and the solar wind, as well as the solar wind acceleration. With that perspective, it is necessary to study the phenomena that could allow some structures to survive to large distances from the Sun. If the switchbacks are associated with heating and acceleration mechanisms, they should allow for transfer of energy. That transfer of energy can occur at the boundary of the switchbacks, which are not completely characterized yet. The origin of the reversals is also crucial as it could provide insight about the origin of the solar wind. Indeed, this study would require a comprehensive analysis between in situ measurements of local magnetic reversals and remote observations of the release mechanisms.

1.6.1 Outline of the thesis

First, I focused on the boundaries of the switchbacks, the interval that contains the sharp rotation of the magnetic field. Indeed, they should give direct insight into the origin of the structures as well as into the dynamics of the switchback propagation in the solar wind. This analysis is presented in Chapter 2. The purpose was first to perform a statistical analysis of multiple PSP encounters, to follow the work of Larosa et al. [2021]. The 3D nature of the boundaries revealed a larger complexity than other types of plasma discontinuities. That required a new approach to resolve their nature. Interestingly, I found results in stark contrast with all previous analyses on the switchback boundaries. That brings more constraints to the generation mechanisms. The results also raise new questions about the propagation of the switchbacks in the solar wind. These results have been published in Bizien et al. [2023].

I performed a second analysis reported in Chapter 3, which is focused on the origin of the switchbacks. One of the conclusions of my first work is that it is consistent with the solar origin of the switchbacks. The study does not exclude additional in situ generation. There is still no proof of a switchback generation in the lower corona, but there is a growing consensus that switchback precursors could be related to the numerous small-scale energetic events that originate in the lower corona. The absence of proof lies in the difficulties of connecting in situ measurements from a spacecraft to their solar source region. The higher difficulty level is directly related to the transient nature of the switchbacks, which occur on timescales too short for the connectivity methodology. I will present the most rigorous methodology so far, including most of the uncertainties that are possible to resolve. These results have been submitted for publication as an A&A Letter.

In Chapter 4, I will briefly summarize the main results of the thesis and describe the perspectives for future work.

1.6.2 On the inherent difficulties to work within two communities

After three years working on this PhD thesis, while first starting on in situ solar wind measurements and then moving slowly to the solar physics measurements, I realized that there is a gap between the two communities. On the one hand, the solar physics scientific community is working on understanding solar phenomena, their origins, and their temporal and thermal properties and composition. They have their specific terminology for solar events. These terminologies sometimes depend on the instrumentation and the temporal, spatial, and spectral resolution of the data. This leads to multiple names given to the same phenomenon. Considering the complexity and variety of solar eruptive events, that adds a certain difficulty to understanding the global picture. However, the solar wind plasma physics community is working on in situ measurements of the solar wind at the spacecraft's position. That is mainly done by the use of time-series of different plasma parameters.

What was clear from my literature review is that the two communities lack from more interactions and discussions. Many theories about the origin of switchbacks are based on inconceivable events that would be directly highlighted by the solar physics community. The connectivity between both physics is usually observed in space weather predictions. That is done for large eruptions that may encounter the Earth's magnetic field and is thus of interest. Here, I focus on small-scale energetic transient events. They are fainter events, which increase the difficulty of tracking their path in remote observations.

Switchback boundaries

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2.1 Introduction

2.1.1 Motivation

In Chapter 1, we saw that switchbacks are sudden deflections of the solar wind whose ubiquity in the inner heliosphere has attracted considerable attention. Switchback boundaries correspond to the sharp transition intervals between a quiet background magnetic field and the field inside the structure. They are one of the striking properties of the switchbacks. Interestingly, they can be studied from the perspective of a global understanding of the switchback's interaction with the ambient solar wind. The exact nature of the switchback boundaries is still unknown. However, it should provide some insight into the evolution of switchbacks in the solar wind as they propagate away from the Sun. Are they open boundaries with a possible plasma flow across, or do they prevent any plasma flow, acting as closed boundaries? Their nature could also keep a signature of the origin of the structure and add constraints on the generation mechanisms.

In this chapter, I propose comparing two methods, one of which is frequently used in such analyses, to determine the nature of the boundary. This will be directly related to the specificities of the switchback boundaries compared to the different structures in the solar wind.

The aim of this chapter is to answer the following open questions:

- What is the nature of switchback boundaries?
- How are the properties of the switchback boundaries linked to their dynamical evolution in the solar wind?

The nature of the boundary is of relative importance for a certain number of questions about the switchbacks. First, their nature is directly related to the propagation of the switchbacks in the solar wind. Ultimately, this will impact the survival of the switchbacks, which is directly linked to the nature of the boundary. If they are open structures that allow for exchanges of mass and energy, they can be eroded faster during their propagation. When one links this question to the presence of switchbacks at larger distances from the Sun, a first theory may imply an in situ generation of a sub-population of switchbacks or even of all switchbacks. Then, the nature of the

switchback boundaries can bring constraints on the generation of the structures. A second theory is that only certain types of switchback survive until larger distances, and these should then have different properties. The previous reasoning is not directly related to the boundaries as is discussed is the propagation and possible survival of the switchbacks. However, in that perspective, mechanisms that can destroy the structures should be investigated. These mechanisms may occur directly at the boundary. The signatures of erosion are still rare in the measurements. This could be linked to the nature of switchbacks, as we detect a certain type of boundary that may prevent the erosion mechanisms. This Chapter includes the original results published in [Bizien et al. \[2023\]](#), and more in-depth interpretation of the results to understand the behavior of switchbacks.

2.1.2 MHD plasma discontinuities

Let us introduce the terminology and parameters that will be used in this analysis to determine the nature of the switchback boundaries. The boundaries of switchbacks are characterized by an abrupt change in the magnetic field, a plasma discontinuity. A discontinuity is defined as a separation between two plasma regions with different properties. In the MHD approximation, such discontinuities in the solar wind are routinely described by means of the Rankine-Hugoniot relations, introduced here.

The notation $[X] = X_2 - X_1$ corresponds to the difference of the quantity X between the two sides of the discontinuity. We take that the surface of the discontinuity has a normal $\mathbf{n}$ and moves at a relative speed $\mathbf{U}$. The t subscript then denotes the component tangential to the surface. We then assume that the surface is an infinite plane, so $\mathbf{U} \cdot \mathbf{n}$ is the only component of $\mathbf{U}$ that has physical significance. We finally assume time stationarity in the discontinuity rest frame and that the spatial variations occur in the normal direction.

The plasma densities ρ_1 and ρ_2 , the bulk velocities $\mathbf{v}_1$ and $\mathbf{v}_2$, the magnetic fields $\mathbf{B}_1$ and $\mathbf{B}_2$ and the plasma pressure $p_{\parallel}$ and $p_{\perp}$ are known.

The conservation of mass, momentum, energy, as well as the tangential component of the electric field and the normal component of the magnetic field gives the following jump conditions at the discontinuity [[Hudson, 1970](#)]:

$$[B_n] = 0, \quad (2.1)$$

$$[\rho(\mathbf{v} - \mathbf{U}) \cdot \mathbf{n}] = 0, \quad (2.2)$$

$$B_n[\mathbf{v}] = G[\mathbf{B}/\rho], \quad (2.3)$$

$$\left[p_{\perp} + \frac{B^2}{2\mu_0} + \frac{G^2}{\rho} - \frac{B_n^2}{\mu_0} \left(1 - \frac{(p_{\parallel} - p_{\perp}) \mu_0}{B^2} \right) \right] = 0, \quad (2.4)$$

$$\left[G\mathbf{v}_t - \frac{B_n\mathbf{B}_t}{\mu_0} \left(1 - \frac{(p_{\parallel} - p_{\perp}) \mu_0}{B^2} \right) \right] = 0. \quad (2.5)$$

where $G \equiv \rho_1 (\mathbf{v}_1 - \mathbf{U}) \cdot \mathbf{n} = \rho_2 (\mathbf{v}_2 - \mathbf{U}) \cdot \mathbf{n}$ is the mass flux normal to the discontinuity. These equations are the necessary conditions for any jump in the plasma.

The main distinction between the discontinuities depends on the value of G , which is then related to the dynamic of the discontinuities relative to the ambient plasma. The discontinuity can be stationary ($G = 0$), i.e. it does not propagate in the plasma. In this category fall the Contact Discontinuity (CD) and the Tangential Discontinuity (TD). On the other hand, the discontinuity with $G \neq 0$ can be propagating, which corresponds to a fast shock, slow shock, or Rotational Discontinuity (RD) [Hudson, 1970].

In the following work, I do not consider the CD, nor the shocks. CD are structures with relatively few observations. The hypothesis is that CD do not conserve the sharp transition due to the rapid diffusion of plasma along the magnetic field lines across its surface. Then CD would rapidly disappear [Hudson, 1970]. Moreover, there is no jump in the magnitude of the magnetic field in the switchback boundaries, so the switchback boundaries are not shocks.

TDs are convected structures. The magnetic field component is tangential to the structure $B_n = 0$. The jump conditions are simplified as $v_n = 0$. The last non-trivial condition to satisfy is:

$$\left[p_{\perp} + \frac{B^2}{2\mu_0} \right] = 0. \quad (2.6)$$

The total pressure is conserved for TDs. Any other change is arbitrary. An example of how the magnetic field can change for a TD is shown in Figure 2.1. As the field is tangential, the discontinuity separates two plasmas that are not magnetically connected and thus can be of different composition. They also do not allow for particle transport across the discontinuity. The non-propagating properties imply that $U = \mathbf{U} \cdot \mathbf{n} = \mathbf{v} \cdot \mathbf{n}$.

On the contrary, RDs propagate with the Alfvén velocity $\mathbf{V}_A$. They are isentropic, and they have a non-zero normal component of the magnetic field $\mathbf{B}_n \neq 0$. They allow for particle transport, with a finite mass flow across the discontinuity $\rho v_n \neq 0$ and a continuous normal flow velocity $[v_n] = 0$. They have different conditions depending on the anisotropy of the plasma, defined by the firehose factor: $A = 1 - (p_{\parallel} - p_{\perp})\mu_0/B^2$. For an isotropic plasma ($A = 1$) the conditions are then [Baumjohann and Treumann, 2012]:

$$[B] = 0, [B_n] = 0, [\rho] = 0, [p] = 0, [\mathbf{v}_t] = \pm[\mathbf{B}_t]/\sqrt{\mu_0\rho}. \quad (2.7)$$

The last condition is often called the Walén relation [Walén, 1944].

As the derived properties of TDs and RDs are numerous, there are a variety of possibilities to distinguish the two types of discontinuities. For an isotropic wind, the RDs conserve B and ρ . However, the solar wind is not always isotropic. About the TDs, there is no constraint on the magnitude of the jumps in magnetic field and density, which can then be small. The requirement on the jump is on the total pressure that should be constant. A method to distinguish an RD from a TD could be to test the Walén relation, which is characteristic of RDs. However, it is not a sufficient condition to distinguish RDs from TDs, as some TDs could satisfy this condition.

The optimal method is to find a large magnetic field normal component B_n , which would prevent the discontinuity from being tangential. This is the strategy that I will

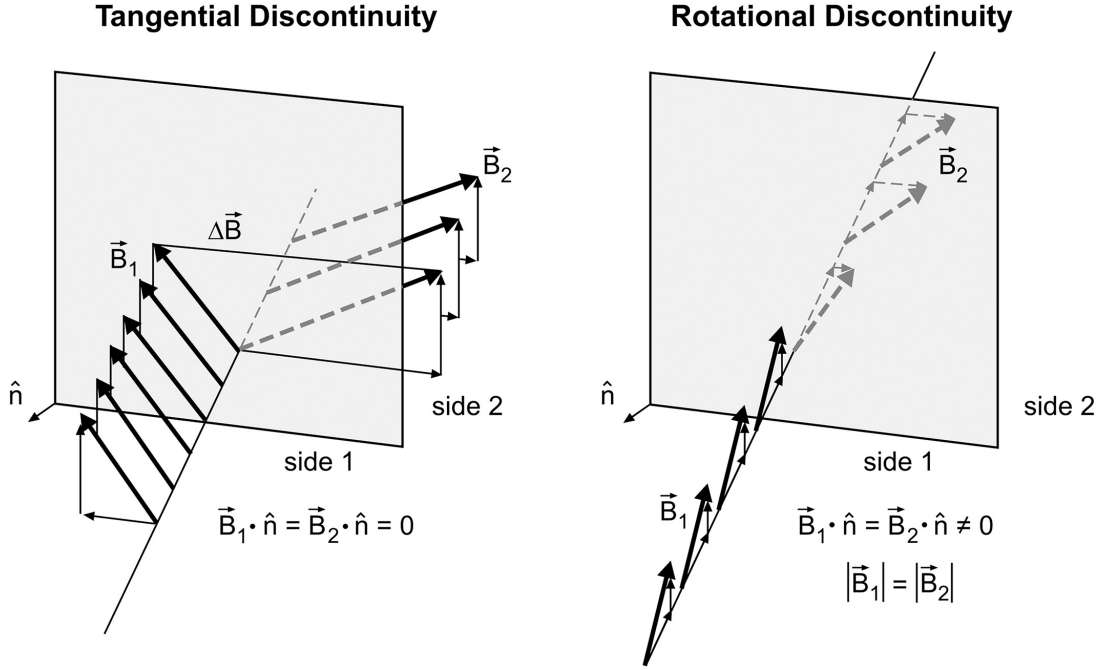


Figure 2.1: Illustration of a TD (left) and a RD (right). The discontinuity is represented by the shaded plane, with its normal $\hat{n}$. Reproduced from [Tsurutani et al. \[2018\]](#).

implement in this chapter, applied to the switchback boundaries. Let us first present the measurements of the switchbacks that will allow characterizing the boundaries intervals.

2.2 In situ measurements of Switchbacks by PSP instruments

2.2.1 A typical switchback

This first section defines a typical switchback measured by PSP, which will serve as an example for our discontinuity analysis. In Figure 2.2, I present a typical switchback with well-defined boundaries. The boundaries are sharp and do not contain embedded substructures. The field moves from a quiet region (before) to another region (during) forming a sharp transition, which we define as the switchback boundary. Then, the field returns to another quiet region (after) with another sharp boundary. The evolution of the proton velocity shows a high correlation with the magnetic field, which is typical for Alfvénic structures and has been observed for many switchbacks [[Kasper et al., 2019](#); [Horbury et al., 2020](#)]. In this example, the maximum deflection with respect to the Parker spiral is approximately 66° .

Throughout the analysis, I use the RTN coordinate frame: the radial R vector is along the Sun-spacecraft direction, taken anti-sunward; the T component is the

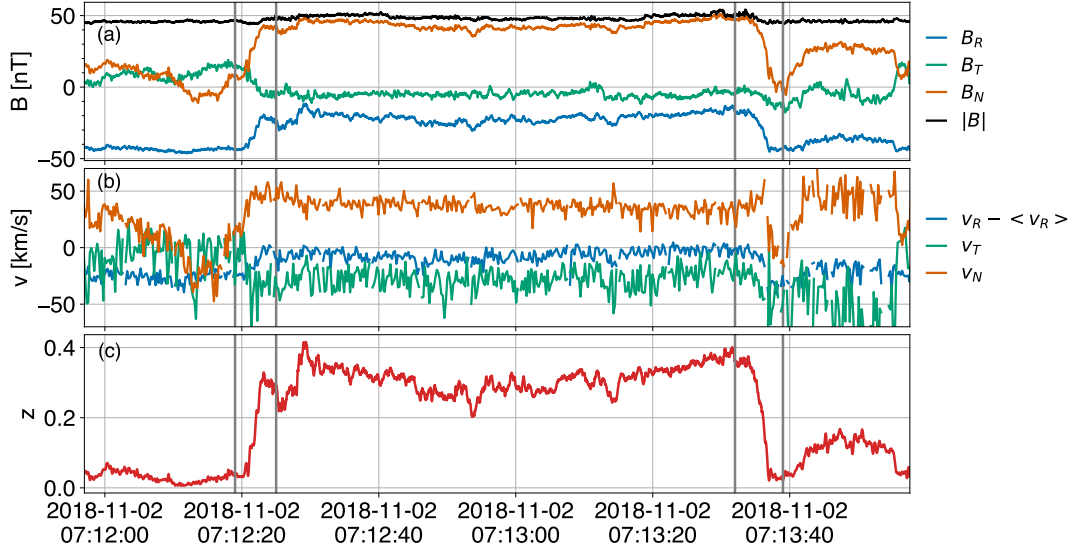


Figure 2.2: Example of a typical switchback. The leading and trailing boundaries are located between the pairs of vertical lines. (a) MAG magnetic field data in the RTN frame; (b) proton velocity from Solar Probe Cup (SPC), also in the RTN frame. The average value of the radial velocity has been removed to facilitate visualization; (c) normalized deflection z . Reproduced from Bizien et al. [2023].

tangential vector, the result of the cross product of the solar rotation vector with R ; and the normal N component, which completes the right-handed triad.

As I call it a typical switchback, I want to argue that there is no typical switchback. Most of the switchbacks measured by PSP are complex structures and move away from the simple square shape. The sharp deflection is a recurrent property, but they may include some substructures or waves. Similarly, the "inside" of the structures may be complex with inside discontinuities. Figure 2.3 presents other examples of switchbacks that show more complexity than the 'typical' switchback. The first panel shows a small deflection with a relatively smoother transition region. The second panel shows a complex structure with wave-like oscillations at the leading boundary. The trailing boundary appears to have substructures. The third panel shows a switchback with numerous substructures and discontinuities embedded in the overall structure.

2.2.2 Magnetic field measurements

The magnetic field measurements of this work are taken from the Fluxgate magnetometer MAG part of the FIELDS suite [Bale et al., 2016] on board PSP. In the first chapter, I introduced the suite that is composed of multiple instruments. Now, I will introduce the characteristics of the instrument. The MAG instrument is located on a 4-meter boom at the rear of the spacecraft. It is protected by the heat shield. The MAG instrument is composed of two instruments, MAGi and MAGo. The redundancy

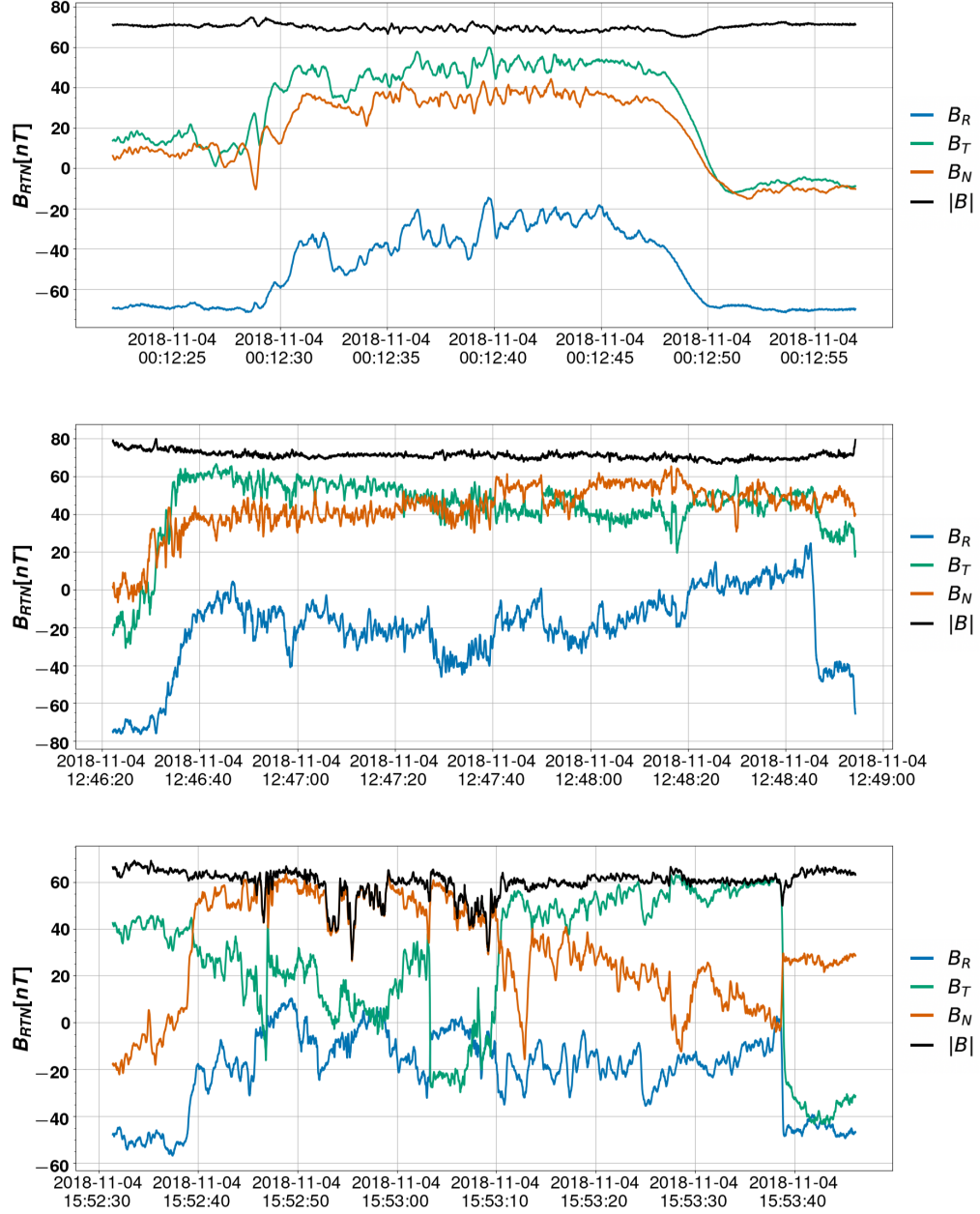


Figure 2.3: Examples of switchbacks observed in the MAG magnetic field data in the RTN frame. The first panel shows a small deflection with smoother rotation. The second panel shows a complex structures with waves at the boundary. The trailing boundary appears to present substructures. The third panel shows a switchback with numerous substructures and discontinuities embedded in the overall structure.

is necessary to determine the magnetic fluctuations that are generated by the spacecraft itself. They are built by NASA/GSFC, with heritage from previous missions (e.g. Solar TERrestrial RELations Observatory (STEREO)) [Bale et al., 2016]. The principle of a fluxgate magnetometer is based on the measurement of the local magnetic field through the electromagnetic force induced by the change of the magnetic flux direction [Acuña, 2002; Miles et al., 2018]. First, a highly permeable core concentrates the ambient magnetic field. The field is channeled through the core and produces a high flux due to the high permeability. When the core is saturated, the permeability falls so that the flux collapses. The orientation of the core is governed by an external excitation core that periodically alternates direction. Then, the core saturates in opposite directions. The flux from the ambient field is always in the same direction. This net flux induces a voltage, according to Faraday’s law. The fluxgate magnetometer only measures the low-frequency magnetic field fluctuations in the range from DC to about 100 Hz.

The nominal cadence of the instrument is 293Hz, but the cadence can be lowered to reduce the size of the data, for telemetry reasons. Thus, I resampled the measurements to 293Hz for the full duration of the encounter.

2.2.3 Determination of the Parker spiral

There are many different possibilities to define the switchback angle. The angle of the deflection depends on the reference taken for the measurements. Some studies are taking the background field B_0 determined in the data [Dudok de Wit et al., 2020; Bale et al., 2019]. The idea is to extract the measurements of the Parker spiral out of the fluctuations through statistical computations such as mean, median, or mode. Some other studies compute the theoretical model of a Parker spiral [Horbury et al., 2020; Fargette et al., 2021] or assume an ideal radial magnetic field [Larosa et al., 2021]. Both types of method show some limitations. Indeed, the identification of the measurements of the Parker spiral from the data may be more difficult, because of the switchbacks themselves. That would highly depend on the amount of relatively quiet intervals without deflections. On the other hand, models are also approximating the background direction, as the ideal Parker spiral equation may not represent closely the actual background field direction.

The decision for this work is to work with an estimation of the Parker spiral from the data. This follows the work in Dudok de Wit et al. [2020], which led to the creation of a catalog that will be used in this chapter. Then, I will obtain the closest estimation of the deflection angle of switchbacks as the one provided in the catalog. The catalog is introduced in a later section (see Section 2.2.5).

In this work, I implement an estimation of the magnetic field background, close to a Parker spiral radial field, starting with the quiet intervals when there is no switchback found in the solar wind measurements. To identify these periods, I first computed the magnitude of the magnetic field over the full encounter and removed the intervals with variations of more than 15% of the median value of the magnitude over a day. The first intention is to remove points that could correspond to structures in the solar wind, and

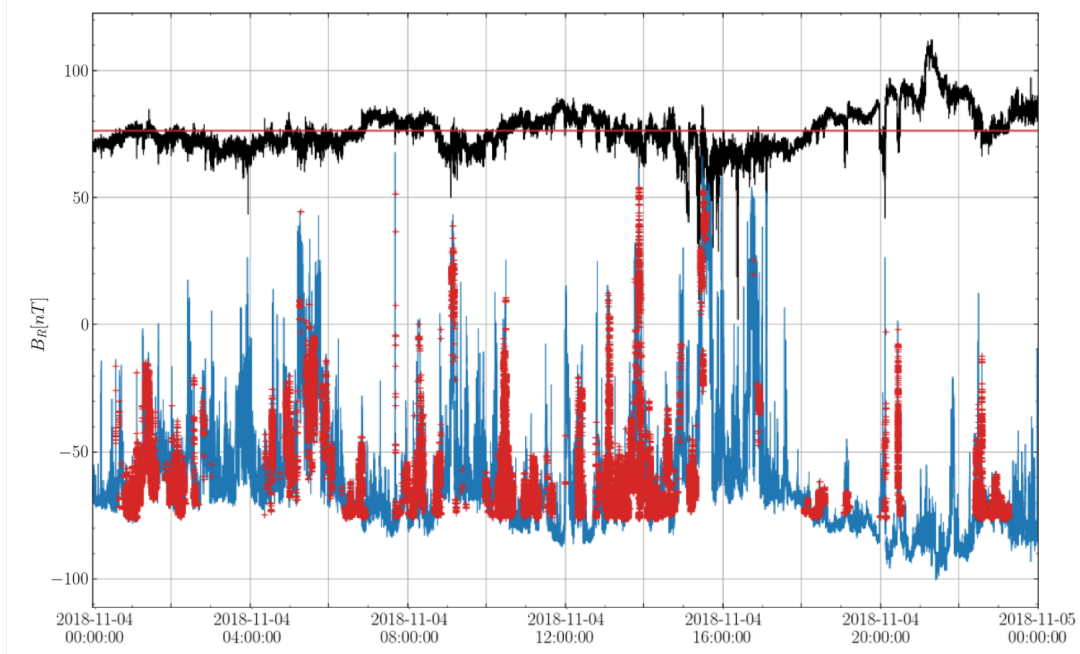


Figure 2.4: Radial magnetic field in blue, measured for one day during E01. In black is the magnitude of the magnetic field whose median magnitude used for the selection of quiet intervals determination is shown with the red line. The red crosses correspond to all the measurements which respect the criterion of almost constant field.

secondly, as I normalize later the components to this value, I will not create artificial peaks in the data. Figure 2.4 shows the selection of points that correspond to the above criterion on one day of Encounter 01.

Then, I remove the intervals when $B_R/|B|$ is less than 0.85 and $B_T/|B|$, $B_N/|B|$ greater than 0.15. This should keep the radial field only and remove the intervals with fluctuations in the TN plane. The parameters were selected to conserve a maximum number of points for the estimation of the spiral without including potential small deflections. Figure 2.5 shows the measurement points that correspond to the above criterion, including the subselection with the field magnitude.

Taking into account the points included in the selection, I compute a median magnetic field per hour. Then I fitted a curve through these hourly values, which I then considered to be the Parker spiral direction. Figure 2.6 shows the slope and the median points for the radial component of the magnetic field. Different fits are shown, linear interpolation, polynomial fit, and median spline. I decide to use a linear interpolation which I smooth using Gaussian over 3h. The edge effects observed on the figures are taken into account and removed.

I then use a normalized deflection from the Parker spiral [Dudok de Wit et al., 2020] to manually identify each switchback boundary in MAG data:

$$z = \frac{1}{2}(1 - \cos \alpha), \quad (2.8)$$

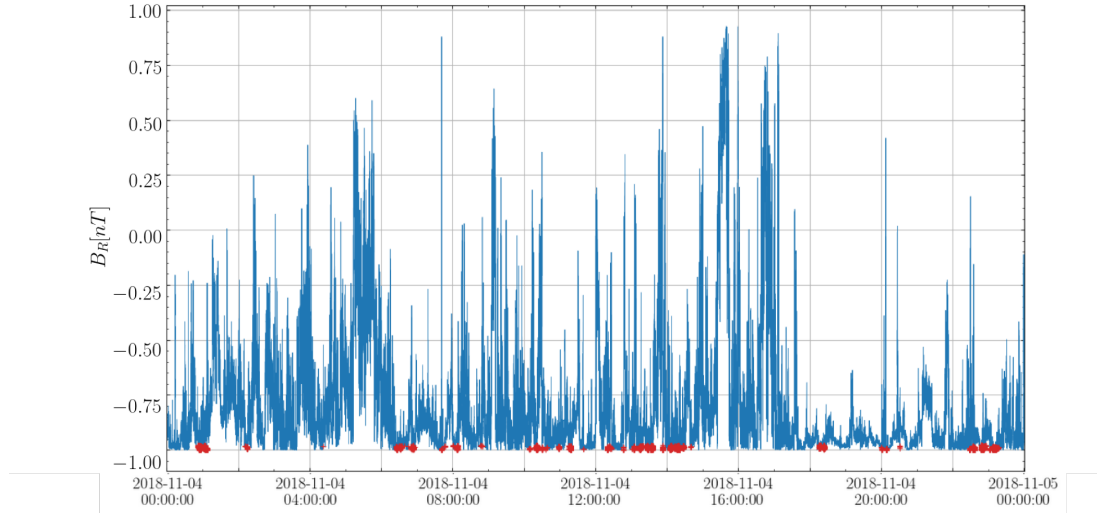


Figure 2.5: Radial magnetic field in blue, measured for one day during E01. The component is normalized to the magnitude of the magnetic field vector. The red crosses correspond to measurements which respect all the criterion on the constant magnitude and almost purely radial field.

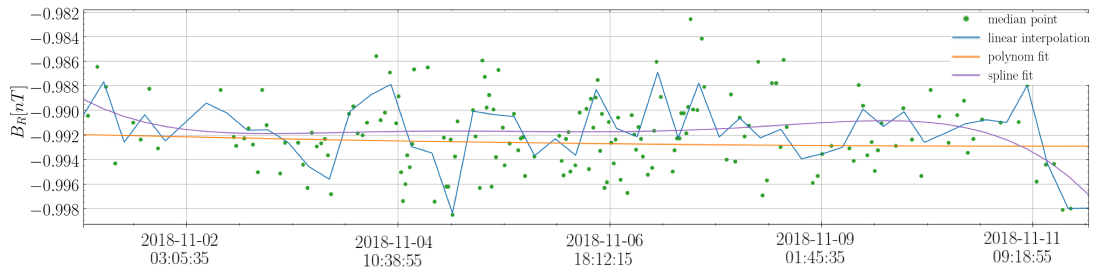


Figure 2.6: Illustration of the determination of the Parker spiral direction. In green are the median estimation per hour. Then different fits are computed to determine the best interpolation.

where α is the deflection angle between the measured magnetic field vector and the direction of the Parker spiral, identified previously. This will be used in the selection of the switchbacks in Section 2.2.5.

2.2.4 Solar wind particles measurements

While magnetic field measurements are, in theory, easier to produce, the solar wind particle measurements are a bit more complex. In this work, I am mostly interested in the proton velocity. I will also use the proton density measurements for an estimation of the local Alfvén velocity. Onboard PSP, there is the SWEAP suite [Kasper et al., 2016], which contains several instruments that measure the velocity and density of ions and electrons. One of them, SPC, is a Faraday cup instrument [Case et al., 2020]. It measures ion and electron fluxes and flow angles as a function of energy. The proton velocity is derived for the ion distribution function measured by SPC.

Other velocity measurements are based on a second instrument Solar Probe ANalyzers—Ions (SPAN-I) [Livi et al., 2022], part of the SWEAP suite. It is an electrostatic analyzer. Reconstructed proton velocity data products are provided from the velocity distribution functions.

What differs between the two instruments, apart from their general construct, is their location on the spacecraft. SPAN-I is located on the ram side of the spacecraft, protected by the heat shield, while SPC measures electrons and ions directly without interaction with the spacecraft. Thus, SPAN-I is highly dependent on the Field Of View (FOV) of the instrument. That needs to be investigated before using the SPAN-I data. A diagnostic of the peak of the velocity distribution function should be performed to ensure that the FOV is capturing more than half of the velocity distribution function [Jaye L. Verniero, private communications, March 19, 2024].

Some interpretations of the velocity measurements should be taken with caution. Several concerns may be flagged, but this does not necessarily indicate that the measurements are unreliable. I primarily use data without flagged concerns, which results in periods with gaps in the measurements. This, in turn, reduces the number of cases that can be investigated.

As presented in Chapter 1, the pitch angle of strahl electrons provides a convenient topology indication, which is necessary to distinguish switchbacks from any HCS crossing. The distribution of the strahl electron pitch angle comes from the Solar Probe ANalyzers—Electrons (SPAN-E) instrument [Whittlesey et al., 2020]. SPAN-E instrument is an electrostatic analyzer. The publicly available data has a low cadence, with bins of 30 seconds. As I am interested in short-duration intervals, this may be limiting in the interpretation of the switchback topology and remove the apparent reversal in the magnetic field measurements from the database. An example of strahl pitch angle measurements during the crossing of a switchback is presented in Figure 2.7. It shows the constant pitch angle at 180° , indicating the field lines' bending.

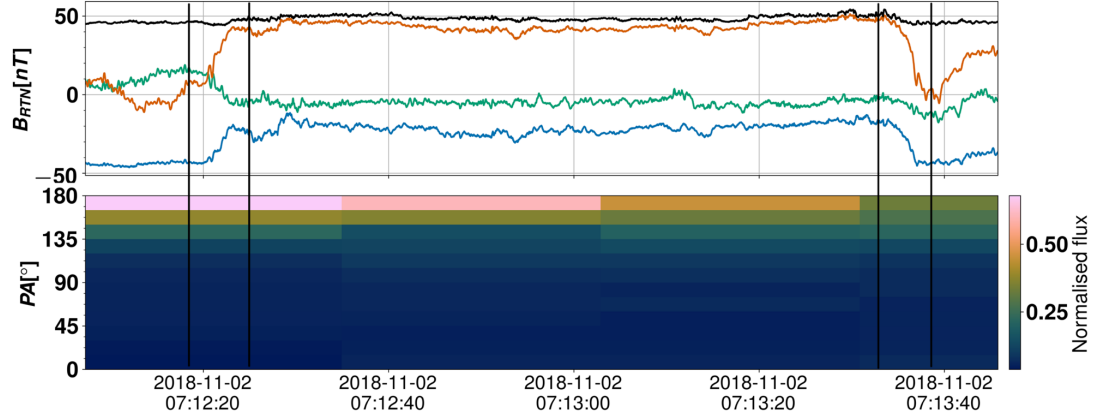


Figure 2.7: Same example of a typical switchback boundary as shown in Figure 2.2. It shows the measurements of the pitch angle of strahl electrons during the crossing of the structure.

2.2.5 Selection of switchback boundaries

Two possible way can be implemented to study the switchback boundaries and to identify them in the data, either using an automatic detection method or based on a manual identification. As they are numerous, one can be tempted to find an automatic detection of the boundary interval. First, one would need to find a threshold for the deflection duration and sharpness compared to other timescales. Then, a constant or adaptive interval around the sharp deflection can be selected. However, that would still need to be checked manually, or that would prevent the study of complex boundaries. Most boundaries are more complex than the example shown in Figure 2.2. Automatic detection can also be critical as there would be a real bias in the normal [Liu et al., 2022b]. This will be discussed in Section 2.3.5. I suggest manually selecting each boundary to reduce the risk of incorrect identification of the normal to the plane of the boundary. A comparative work on the influence of the manual selection by different users was carried out with the supervision of the internship of Ghadir Ollaic (M1) and co-supervision of Tristan Vergé (M2), master students at the University of Orléans. I also performed an analysis using different lengths of interval around the discontinuity. That is discussed in Section 2.4.6.

The selection of the switchbacks that will be analyzed in this work is based on a catalog of switchbacks [Dudok De Wit et al., 2024]. The catalog is filled with deflections detected automatically in the time-series. The method is based on a multiscale pulse shape identification applied to the deflection of the magnetic field from the Parker spiral. The catalog is then based on the z parameter introduced previously, with an estimation of the Parker spiral as a reference. The strahl electron pitch angle is checked to remove polarity inversions. The catalog does not provide an identification of the boundaries intervals. Figure 2.8 shows four switchbacks identified in the PSP time-series, with the rectangular shape as the ideal reference.

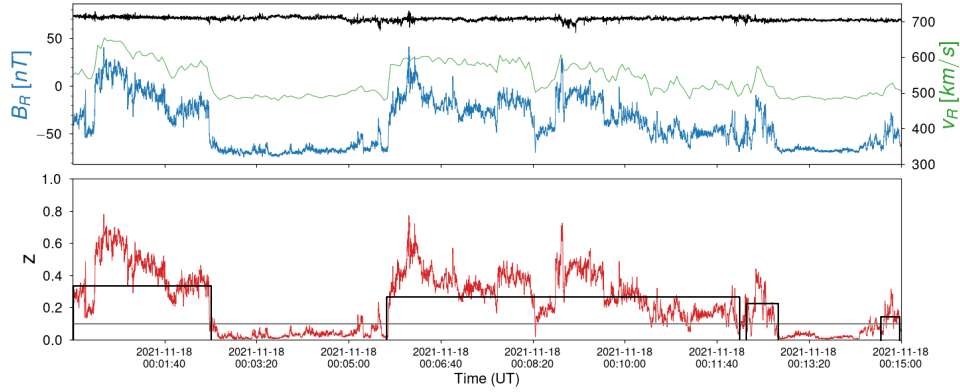


Figure 2.8: Example of a switchbacks interval with the illustration of their identification using rectangular shapes in black. The top panel is the FIELDS/MAG magnetic field data in the R direction, and the proton velocity from SWEAP/SPAN-I is also in the R direction. The bottom panel is the normalized deflection z with the overlapped rectangular shapes representing the structures included in this analysis that are sudden/sharp deflections. Reproduced from Bizien et al. [2025].

I developed a tool to manually select the switchback boundary interval. First, a selection in the catalog is performed, removing the short deflections, as well as those with a small rotation angle below the noise threshold. The switchback minimal parameter z is then set to 0.1, which corresponds to the angle above 36° , as discussed in Chapter 1. The switchback minimal duration should be set to 3 seconds as shorter deflections could be something other than a switchback. I keep only the deflections with sufficient quality from the given quality in the catalog. The best quality shows the deflections close to perfect square deflections, with sharp boundaries. Some switchbacks are discarded when their boundary is too complex to define a boundary interval. In the end, I got 125 switchbacks for this analysis, during the first encounter of PSP, between November 01, 2018, and November 10, 2018. During that interval, the catalog gave 1029 switchbacks. The 125 switchbacks have both boundaries respecting the conditions for the selection.

2.3 Methods

2.3.1 Normal vector definition

In the simple theory presented by Sonnerup and Cahill Jr. [1967], the divergence-free magnetic induction field forces the normal component of the magnetic field to be continuous across an interface with finite thickness, with the condition of the thickness to be smaller than the radius of curvature of the interface. Thus, only three magnetic field measurements are needed to fully resolve the normal vector to a plasma discontinuity: two field vector measurements on each side of the layer and one inside the layer. They

are referred to as $\mathbf{B}_b$ for the measurement before the crossing, $\mathbf{B}_a$ for the measurement after the crossing, and $\mathbf{B}_d$ for the measurement during the crossing of the layer [Sonnerup and Cahill Jr., 1967].

$$\mathbf{B}_b \cdot \mathbf{n} = \mathbf{B}_a \cdot \mathbf{n} = \mathbf{B}_d \cdot \mathbf{n}, \quad (2.9)$$

We can then obtain the normal $\mathbf{n}$ by using the cross product of two vectors that are tangential to the discontinuity

$$\mathbf{n} = \pm(\mathbf{B}_b - \mathbf{B}_a) \times (\mathbf{B}_b - \mathbf{B}_d). \quad (2.10)$$

2.3.2 3D representation of the discontinuity

As a way to understand the complex nature of the discontinuity, it is useful to use a 3D representation, namely hodograms. It corresponds to a curve in space that is obtained from the field vector drawn from the origin. Their direction and lengths are the measurements of $\mathbf{B}$ during the complete discontinuity interval. Then, the hodogram shows only the line that connects the tips of the vectors, following the sequence at which they are measured. Then they are usually shown in two orthogonal planes. However, the complexity of the switchback boundaries is better retrieved with a 3D representation. Figure 2.9 reveals an example of a switchback boundary captured during Encounter 01 of PSP.

The switchback boundaries show a specific feature of alfvénic structures that distinguishes them from most other plasma discontinuities. The magnitude of the magnetic field is conserved in the structures, showing small variations (less than 20% in the observations) [Larosa et al., 2021]. This is verified during the boundary interval for this specific example. However, some structures present dips at their boundaries, with decrease of the magnitude [Farrell et al., 2020]. The tip of the field vector rotates on the surface of a sphere, as observed in Figure 2.9. The radius of the sphere is the magnitude of the field. Moreover, another constraint is added for this rotation. It does not correspond to any random walk on the surface of the sphere, but it is also contained in a plane.

The combination of the two constraints gives a specific structure that is found in the literature as arc-polarized waves [Tsurutani et al., 1997]. The discussion arises from the difference between planar and spherical waves, for which the field magnitude is conserved. This is visible in Figure 2.10. The linear polarization is of interest here. For planar waves, the field magnitude is not constrained, so the vector is always contained in the plane. However, when the magnitude of the field is constant, the constraint forces the tip of the vector to be on the surface of the sphere, with the linear polarization becoming an arc polarization with a clear 3D structure.

From the visual inspection of 250 switchback boundaries that I selected during the first encounter of PSP, I observe that all behave as arc-polarized structures, which rotate on a sphere of constant $|\mathbf{B}|$ while also belonging to a plane that intersects this sphere. These structures are reminiscent of arc-polarized structures that have been

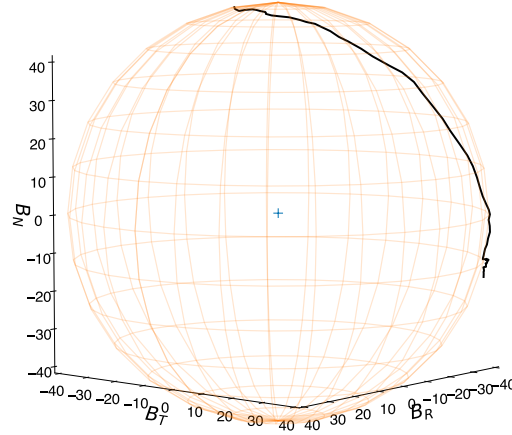


Figure 2.9: Example of a typical switchback boundary. The event was detected on 2018 November 2 at 18:33:33, lasting for 2 s. The deflection from the Parker spiral is about 90° . The black line corresponds to the measurements of the magnetic field during the selected boundary interval. The orange sphere, of radius $|\mathbf{B}|$, represents the (mostly) constant magnitude during the transition interval. The three components of the magnetic field are expressed in nT.

observed in the solar wind near 1 au, and which are spherical in nature [Tsurutani et al., 1997]. Because the boundaries are confined to a plane, their normal is well-defined and can be estimated using Equation 2.10.

The 2D nature of these boundaries represents a strong topological constraint, whose origin has remained elusive so far, as in the case of arc-polarized structures that were observed in the solar wind [Tsurutani et al., 2018]. I will discuss this constraint in Section 2.5.

A second aspect that will have a significant impact on the boundary estimation is the presence of waves at the boundary, as introduced in 1.5.2. Multiple types of waves have been identified [e.g., Krasnoselskikh et al., 2020; Malaspina et al., 2022]. These waves are best detected in the measurements made by SCM, which covers higher frequencies than the MAG measurements used for the boundary analysis. One could be tempted to apply wavelet filtering on the data to remove fluctuations that are not the discontinuity rotation that I want to study [Haaland and Paschmann, 2001]. However, that would also assume that the substructures of the discontinuity are not part of the discontinuity properties that I want to investigate. Using wavelet analyses, many substructures are detected, which may be of different origin. An example will be presented in Section 2.3.4. These waves could also play a role in the erosion of the structures and will be discussed in Section 2.5.6.

The combination of specificities of the switchback boundaries prevents the use of

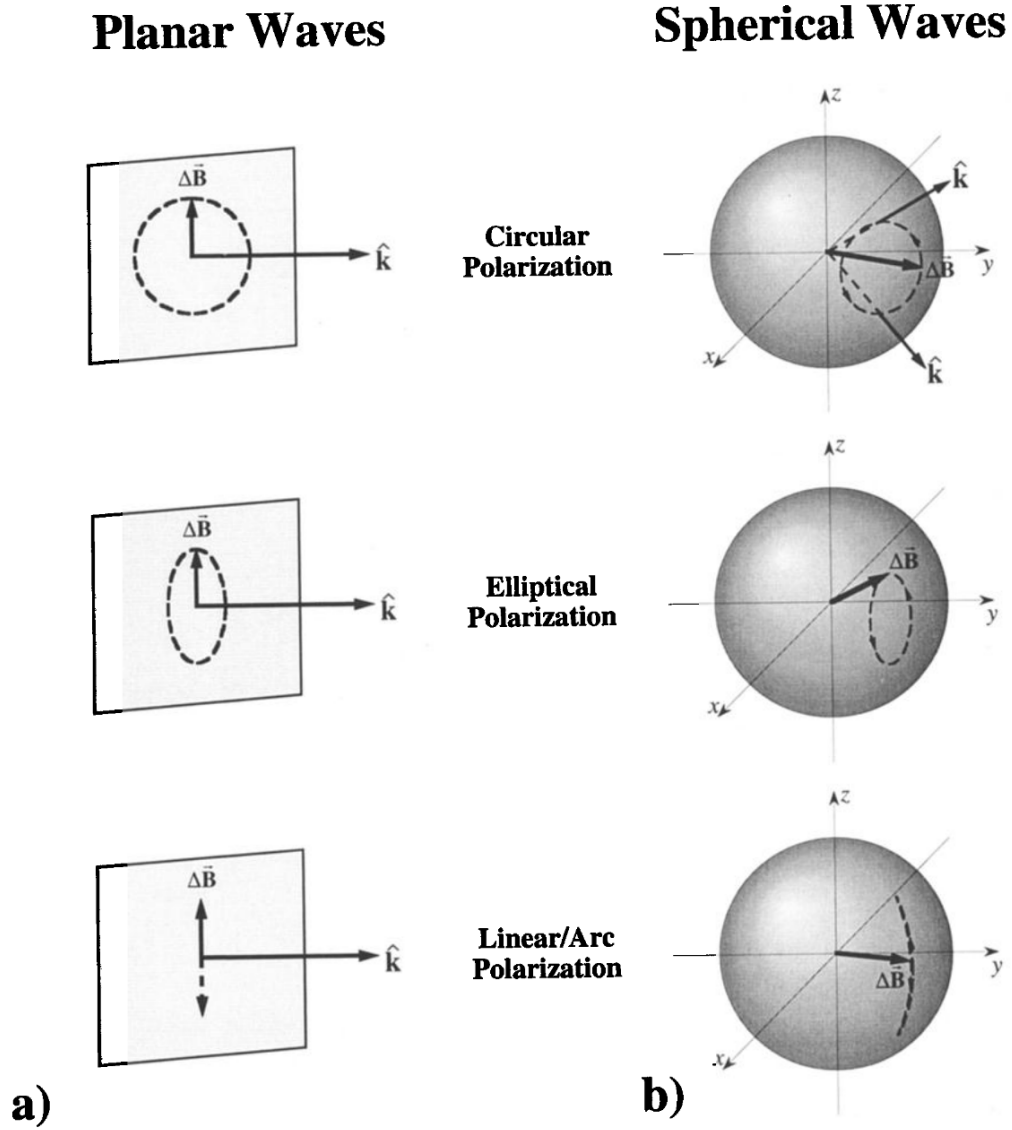


Figure 2.10: Illustration of the polarization differences between planar and spherical waves. Reproduced from [Tsurutani and Ho \[1999\]](#).

Equation 2.10 alone to determine the normal to the boundary. Indeed, the fluctuations would complexify the selection of the three vectors. This explains the necessity to implement more rigorous methods, such as the one presented in the following.

2.3.3 Methods to detect boundaries normal: the Minimum Variance Analysis

Various techniques can be implemented to determine the normal to the discontinuity. It varies with the number of spacecraft measurements and the type of measures. The best characterization of the normal is provided by multi-spacecraft measurements, at least 4, providing a triangulation of the normal. This would still need to assume that the discontinuity is planar and that the velocity is constant between the spacecraft. Constellations with small distances between spacecraft, such as Cluster, may overcome these issues.

When a single spacecraft is available, the normal determination depends then on the type of measurements available. The most commonly used methodology is Minimum Variance Analysis (MVA), which relies on magnetic field measurements. I will implement this method, which is presented in the following section.

The MVA was designed to establish the normal to a transition layer in the plasma, approximated as a one-dimension structure. Here, the application to magnetic field measurements is discussed, but it can also be applied to electric field measurements [Sonnerup and Scheible, 1998]. The method determines the direction in space in which the variance of $\mathbf{B}^{(i)} \cdot \mathbf{n}$ is minimal, for $\mathbf{B}^{(i)}$ the N measurements of the field during the crossing. The normal corresponds then to the direction with a smaller variance, defined by:

$$\sigma^2 = \frac{1}{N} \sum_{i=1}^N |(\mathbf{B}^{(i)} - \langle \mathbf{B} \rangle) \cdot \mathbf{n}|^2 \quad (2.11)$$

The average vector $\langle \mathbf{B} \rangle$ is defined as $\langle \mathbf{B} \rangle = \frac{1}{N} \sum_{i=1}^N \mathbf{B}^{(i)}$, correspond to the mean vector over the N measurements [Sonnerup and Cahill Jr., 1967].

This is equivalent to solving an eigenvalue problem, using a Lagrangian multiplier λ and a normalization constraint $|\mathbf{n}|^2 = 1$. The equation can be formulated as:

$$M^B \mathbf{n} = \lambda \mathbf{n}, \quad (2.12)$$

with the covariance matrix in the eigenvector basis $(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3)$:

$$M_{ii}^B = \langle \mathbf{B}_i \mathbf{B}_i \rangle - \langle \mathbf{B} \rangle \langle \mathbf{B} \rangle. \quad (2.13)$$

Then, the allowed λ are the eigenvalues of the covariance matrix, with $\lambda_1 \geq \lambda_2 \geq \lambda_3$. The covariance matrix is symmetric, which gives real eigenvalues and orthogonal eigenvectors. Then, the direction of maximum, intermediate, and minimum variance of the magnetic field components are given along the three eigenvectors, while the corresponding eigenvalues represent the variance in the components.

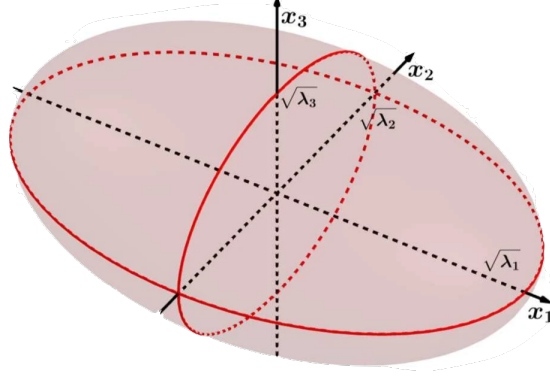


Figure 2.11: The variance ellipsoid. The three eigenvectors $\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3$ are the principal axes of the 3D ellipsoid, whose semi-major axis are respectively $\sqrt{\lambda_1}, \sqrt{\lambda_2}, \sqrt{\lambda_3}$. Reproduced from Rosa Oliveira et al. [2020].

In the variance space, defined by the three eigenvectors, the field vector coordinates are defined by $\sqrt{\lambda_i}$. This gives an ellipsoid of equation:

$$\frac{\sigma_1^2}{\lambda_1} + \frac{\sigma_2^2}{\lambda_2} + \frac{\sigma_3^2}{\lambda_3} = 1, \quad (2.14)$$

which is presented in Figure 2.11.

The MVA can, therefore, be understood from a geometrical perspective. It approximates the orbit of $\mathbf{B}$ by an ellipsoid.

The relative magnitudes of λ_i lead to different shapes of the ellipsoid. There are three major types of degeneracies of the variance ellipsoid: $\lambda_1 \approx \lambda_2$; $\lambda_2 \approx \lambda_3$; and $\lambda_1 \approx \lambda_2 \approx \lambda_3$ [Sonnerup and Scheible, 1998]. The second and last degeneracies prevent any conclusion about the direction of the normal to the discontinuity. An interesting case arises when there is a $\lambda_1 \geq \lambda_2 \gg \lambda_3$ degeneracy, which is still valid when $\lambda_1 \approx \lambda_2$, as this corresponds to a 2D or 1D distribution of the orbit of $\mathbf{B}$. This is typical for plane-polarized waves but also occurs with some types of discontinuities. In such circumstances, the third principal axis $\mathbf{x}_3$, along which the variance is smallest, is usually interpreted as the direction of the normal to the 2D structure [Sonnerup and Scheible, 1998], while the two other eigenvectors $\mathbf{x}_1$ and $\mathbf{x}_2$ are tangential to the discontinuity. This is indeed the case for most of the discontinuities discussed in this chapter, including the switchback boundaries. However, that 3D configuration is difficult to retrieve with this technique, even if the conditions appear to be met.

2.3.4 A switchback boundary analyzed with the MVA

The MVA is a widely used method to identify the normal to the discontinuity plane. It is relatively easy to implement, but it shows numerous deficiencies. My study focuses on switchback boundaries, which differ from the discontinuities mostly investigated with the use of MVA. However, most of the studies do not focus on switchback boundaries.

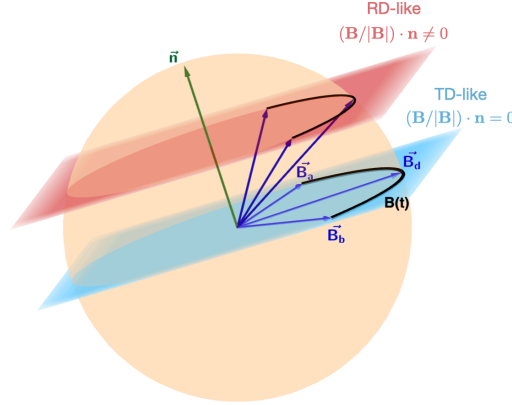


Figure 2.12: Schematic view of an arc-polarized switchback boundary. The three vectors are from Equation (2.10). The blue plane represents the discontinuity plane in which the tips of the field vector rotate, with its normal $\mathbf{n}$ in green. This is a particular event for which the plane includes the origin. The orange sphere, of radius $|\mathbf{B}|$, represents the constant magnitude during the transition interval. A more general arc-polarized boundary is shown, with the identified plane in red. Both planes have the same normal. It should be noted that the two cases are ideal boundaries. Measured switchback boundaries would not have $(\mathbf{B}/|\mathbf{B}|) \cdot \mathbf{n} = 0$ exactly, mainly because of fluctuations. Reproduced from Bizien et al. [2023].

This section includes my analysis of switchback boundaries but also a discussion of the MVA applied to general discontinuities in the solar wind.

As discussed previously, the boundaries of switchbacks are arc-shaped structures with a clear rotation of the magnetic field. However, boundaries are, in general, more complex because they include superimposed waves. Such an arc-shaped structure can be defined as the intersection between the sphere of constant radius $|\mathbf{B}|$ and a plane that cuts it, as illustrated in Figure 2.12. From Equation 2.10, the boundary normal $\mathbf{n}$ is perpendicular to this plane, i.e., essentially perpendicular to $\mathbf{B}$. In the figure, both planes share the same arc-configuration and the same normal. Logically, one would expect the MVA to detect this plane because it is the only one that contains the orbit. I will now present the investigation of a switchback boundary. Figure 2.13a) shows the orbit of the magnetic field for the leading edge of a switchback identified in the magnetic field waveforms, as obtained by MAG. For this particular case, I find $\lambda_1/\lambda_2 = 11.4$ and $\lambda_2/\lambda_3 = 2.1$. I will discuss the criteria about the ratios in the following section.

Given the observed ratios, which satisfy most of the criteria required for MVA reliability, one might be tempted to conclude that the orbit is reasonably close to 2D and therefore the normal should coincide with the third principal axis. As it turns out, this conclusion is completely misleading.

I find a completely different result: the MVA detects a plane that is tangential to the surface of the sphere, shown in red in Figure 2.13a. The boundary normal given

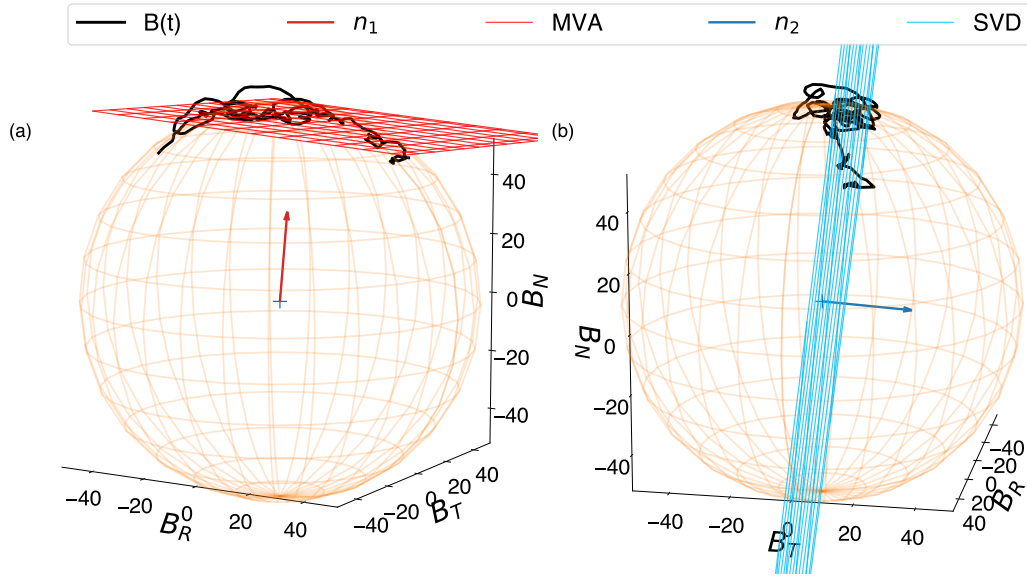


Figure 2.13: Example of a typical switchback boundary in the RTN frame on November 7, 2018, at 20:53:15, which lasts 3s. The maximal deflection from the Parker spiral is about 104° . The black line corresponds to the measurements of the magnetic field during the selected boundary interval. The orange sphere, of radius $|\mathbf{B}|$, represents the (mostly) constant magnitude during the transition interval. The view is rotated between the two panels. Panel (a) shows in red the discontinuity plane identified by the MVA, with its normal $\mathbf{n}_1$ in red. Panel (b) shows in blue the discontinuity plane identified with the alternative method (Singular Value Decomposition (SVD), see Section 2.3.7), with its normal $\mathbf{n}_2$ in blue. Reproduced from Bizien et al. [2023].

by the [MVA](#) points in the radial direction and therefore tends to be aligned with the magnetic field. This situation prevails for most of the 125 switchbacks that I have analyzed.

2.3.5 Deficiencies in the MVA implementation for switchback boundaries

2.3.5.1 Fluctuations

The ill-determination of the boundary normal has to do with fluctuations. Such fluctuations cause the orbit to deviate from a regular arc to a structure with fluctuations on a sphere. Because of the high Alfvénicity, the trajectory tends to remain on the surface of the sphere. When the deflection is small, this orbit defines a band-like structure, which the [MVA](#) tends to identify as the plane of the discontinuity, especially when the arc-shaped orbit is difficult to disentangle from fluctuations. In fact, if the plane of polarization of the wave is perpendicular to the discontinuity, the [MVA](#), by construction, will identify the plane that includes these variations and not the transition plane. The plane of polarization refers to the plane that includes the direction of propagation of the wave as well as the direction of the magnetic field.

These issues were revealed in previous studies of discontinuities with substructures, but also in the specific case of arc-polarized structures. [Haaland et al. \[2012\]](#) analyzed discontinuities with wavelet analysis and determined that when 2D or 3D structures are observed inside the discontinuity, as well as a large value of $(\mathbf{B}/|\mathbf{B}|) \cdot \mathbf{n}$, the [MVA](#) provides a poor estimate of the normal. [Tsurutani and Ho \[1999\]](#) discussed the use of [MVA](#) for arc-polarized structures. They argue that most of the variance will be in the maximum direction and very little in the intermediate direction. Then the ratio λ_2/λ_3 is close to 1, which means a larger uncertainty in the estimation of the normal.

2.3.5.2 Estimation of the mean value of the magnetic field

Regarding discontinuity analysis, a major limitation of the [MVA](#) comes from the mathematical definition of the principal axes and λ_i . Both are obtained by diagonalizing the covariance matrix of the magnetic field, which requires the prior subtraction of the mean of each of the components of $\mathbf{B}$. For most switchbacks, this mean is strongly dependent on the choice of the time interval around the discontinuity from which the mean is estimated [[Hausman et al., 2004](#)]. This arbitrariness, in turn, affects the value of the mean and the orientation of the normal. [Hausman et al. \[2004\]](#) show that the errors are due to the difference between the normal given by the [MVA](#) and the expected normal. And the reason is that [MVA](#) calculation is not derived from equation 2.10. Moreover, [Barnes \[1976\]](#) states that there are no plane-polarized large-amplitude Alfvén waves, in which $\mathbf{B}$ lies in one plane at all points of the disturbance, and that Alfvén waves with no well-defined minimum direction can be found in principle. This is consistent with the Alfvénic properties of the waves, as the field vector is constrained to rotate on the surface of a sphere. The controversial minimum variance direction

provided by the [MVA](#) is even considered to only be a result of the random variations of the field vector on a sphere around the mean magnetic field direction. There is no influence of the planarity or non-planarity of the structure [[Barnes, 1981](#)].

2.3.5.3 Complexity of automation

I want to add some critical concerns that can significantly affect the study of switchback boundaries using the [MVA](#). They all relate to the selection of the boundary interval, which is crucial. Usually, the transition section is not clear, and the superposition of waves or other substructures is observed in the time-series, as highlighted in the examples presented in [Figure 2.3](#). Including sections before and after the transition that have a high impact on the normal determination, and the [MVA](#) can give wrong plane identification. The speed of the transition is a relevant factor, causing the normal to be ill-determined. For slow transitions, which can last several seconds to minutes, the section corresponding to the transition represents about a third of the total interval selected for the [MVA](#). Thus, the transition has the same weight in the calculation, and it is usually better estimated by the analysis. For example, this situation is found in the switchback presented in the top panels of [Figure 2.3](#). However, when the transition is sharp, which is the case for numerous switchbacks, the transition part is less weighted compared to the before and after sections. The trailing boundary of the switchback in the third panel of [Figure 2.3](#) is an example. Thus, if these “outside” sections correspond to a different plane than the transition, the [MVA](#) will identify this plane and not the plane of the discontinuity intended.

This error was diagnosed from the first analysis of a discontinuity by the [MVA](#) [[Sonnerup and Scheible, 1998](#)]. They show that the eigenvectors $\mathbf{x}_2$ and $\mathbf{x}_3$ can be interchanged by removing only a single point at each end of the interval. That was more important in their data, as the cadence was lower than in our study. Their example included only 15 data points. In our analysis, with the high sampling rate of MAG, we are not limited by the number of measurements during the crossing of the discontinuity. However, some intervals are short, with only 25 points, which is still above the example of [Sonnerup and Scheible \[1998\]](#). Out of the sample of boundaries analyzed in this chapter, 12 present less than 50 measurement points.

In conclusion, the automated application of the [MVA](#) can easily produce boundary normals that are completely different from those obtained by visual inspection, leading to erroneous conclusions.

2.3.6 General issues of the MVA

Although the [MVA](#) already appears to be limiting in the study of the arc-polarized switchback boundaries, I want to highlight that these issues are mostly and usually only discussed by the mean of the eigenvalue ratios. However, this focuses only on technical aspects that can be overlooked compared to the actual construction problem of the [MVA](#) when applied to such structures, as previously stated. A criterion on the eigenvalue ratio λ_2/λ_3 is commonly used to investigate the reliability of the estimation

of the normal by the **MVA**. In fact, when the ratio is small, the uncertainty in the normal estimation is large as it can correspond to any direction in the $(\mathbf{x}_2, \mathbf{x}_3)$ plane, which is equivalent to an 90° error [Sonnerup and Scheible, 1998].

The classical selection criterion for normal identification is $\lambda_2/\lambda_3 \geq 2$ [Lepping and Behannon, 1980]. They noticed that the ratio of the intermediate to minimum eigenvalue has to be greater or equal to 2 to prevent inaccurate normal identification. Any discontinuity that satisfies this criterion is considered as being correctly estimated by the **MVA**. There are a consequent number of publications that discuss these eigenvalue ratios for the interpretation of the results and the conclusion on the nature of the discontinuity. This criterion has been criticized as it is not sufficient to be certain about the normal and plane identification. Some authors recommend using a more stringent criterion $\lambda_2/\lambda_3 \geq 10$, to be consistent with triangulation methods using Cluster data [Knetter et al., 2004]. This is a highly restrictive criterion, as very few discontinuities strictly respect this value. It would prevent the statistical conclusions aimed at in my study. A new criterion was introduced by Lepping and Behannon [1980], using a combination of eigenvalues ratio, $\Lambda = \lambda_3/\lambda_1 + \lambda_3/\lambda_2$. In most cases, $\Lambda \simeq \lambda_3/\lambda_2$, but it should allow detecting cases where the degeneracy $\lambda_1 \gg \lambda_2$ no longer holds.

The discussion of the eigenvalue ratio is sometimes associated with the deflection angle. In fact, Lepping and Behannon [1980] suggests only including deviations from the Parker spiral with an angle above 40° to avoid misinterpretation of the discontinuities. That condition is approximately respected in my analysis, as I only consider deflections above 36° . Horbury et al. [2001] discussed the minimal deflection angle and noticed that if it is smaller than 30° , then the **MVA** normal is systematically parallel to the mean field and not to the normal retrieved by multi-spacecraft methods. They find that the eigenvalue ratio is usually small but still higher than 2. The exact value is not provided. This discussion is not sufficient as larger deflections still present issues with the **MVA**.

Techniques can be implemented to detect these errors such as the bootstrap [Kawano and Higuchi, 1995] or analytical methods based on the eigenvalues [Khrabrov and Sonnerup, 1998]. They may be biased as they rely only upon the eigenvalues ratios.

While the debate appears shifted towards specific criteria that may not represent a physical constraint, multi-spacecraft missions provide a means to verify the validity of the **MVA**, without focusing on the eigenvalues ratio. Indeed, with three or more spacecraft, a triangulation method is applied by timing the discontinuity arrival at each spacecraft, which provides a better estimation of the 3D structure and, thus, the normal of the discontinuity. Horbury et al. [2001] analyzed discontinuities identified by three spacecraft, Geotail, Wind and IMP 8. They find that 57% of the discontinuities are **RDs** with the use of **MVA**. However, 70% of the discontinuities are **TDs** with the more precise triangulation method. Using the normals estimated from the 3 spacecraft timings, the normal component of the magnetic field is small, closer to the properties of **TDs**. They conclude that the discrepancy they find compared to the number of **RDs** found in previous studies is mainly based on the methodology used and not on the influence of the dataset. The comparison of normals provided by the **MVA** and from

timings of multiple spacecraft shows the limitations of the arguments on the eigenvalues ratio to conclude on the validity of the MVA's normal. In fact, they find that with λ_2/λ_3 above 5, the difference between the two normals is still about 50° .

For these reasons, I will not discuss the eigenvalues λ_i in the following analysis, as one would normally do, and instead focus on the geometric representation of the magnetic field vector. One of the main warnings I could give for future normal determination is to investigate the raw observations of switchback boundaries with 3D representation and not rely only on generic eigenvalues ratio.

Now, I will define a more robust method for determining the plane to which the orbit belongs. This is a novel strategy that is well suited for arc-polarized structures and does not imply the use of threshold on eigenvalues ratio nor the use of filtering, which requires some assumptions on the discontinuity.

2.3.7 A different technique for plane fitting

The problem of plane fitting in a high-dimensional space has received considerable attention for over a century [Pearson, 1901] and is routinely solved by means of the SVD [Golub and Loan, 2013]. The starting point for these is a rectangular matrix that contains the three components of the magnetic field. The SVD decomposes such a matrix into a product of three matrices: the first one contains the projection of the magnetic field on each of the three axes of the ellipsoid, the second one contains the values of $\sqrt{\lambda_i}$ and the third matrix contains the principal axes of the ellipsoid, one of which is $\mathbf{n}$.

The MVA is conceptually identical to the SVD. The only difference is related to the mean value of each component of the magnetic field. For the SVD, the mean value is conserved, so the decomposition is applied to the raw magnetic components. For the MVA, the mean value is subtracted before applying the same decomposition as the SVD.

As discussed in the previous section, for switchback boundaries, the MVA tends to find planes that are tangential to the sphere, as in Figure 2.13(a). If we do not subtract the mean and thus apply the SVD, then the plane is forced to include the origin, that is, the center of the sphere $\mathbf{B} = 0$, see Figure 2.13(b).

Therefore, by applying the SVD to the raw data without first subtracting the mean, we force the plane to include the orbit of the magnetic field that describes an arc, shown in blue for an ideal boundary in Figure 2.12 and in Figure 2.13(b) for a switchback boundary. This is a special arc because the plane includes the origin, thus cutting the sphere in half. This arc defines the shortest path on the sphere between its two endpoints, similar to a geodesic. In that case, we have $(\mathbf{B}/|\mathbf{B}|) \cdot \mathbf{n} = 0$.

However, for some structures, the boundary plane clearly does not include the origin, as shown in red for an ideal boundary in Figure 2.12, in which case we have $(\mathbf{B}/|\mathbf{B}|) \cdot \mathbf{n} \neq 0$. In such conditions, as the SVD plane does always include the origin, it will not capture the orbit of $\mathbf{B}$.

For larger deflections, when it is visually easier to identify the arc structures out of

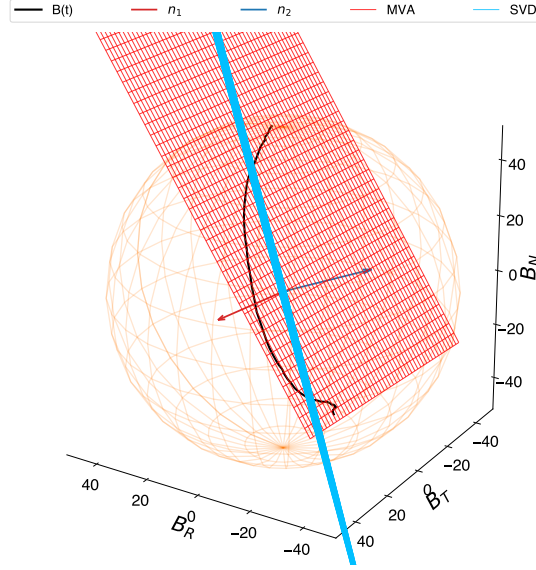


Figure 2.14: Same as Figure 2.13 but for a boundary misidentified by the SVD (blue plane) but correctly identified by the MVA (red plane). The event was detected on November 2, 2018, at 18:33:33, lasting for 2 s. The deflection from the Parker spiral is about 90° . Reproduced from Bizien et al. [2023].

the fluctuations level, the MVA solution becomes unstable. Indeed, it is then highly dependent on the choice of the time interval that corresponds to the computation of the magnetic field mean. Then, for some deflections, mostly large deflections that typically exceed 90° , the MVA switches solutions. It does not detect the plane tangent to the sphere and clearly shows the true plane of polarization, as is the case for the example shown in Figure 2.14. In similar cases, the SVD would not provide the correct estimation of the normal, while the MVA does provide the normal to the boundary.

2.3.8 Geometrical property to determine the nature of the boundary

In conclusion, the nature of switchback boundaries is closely related to a simple but specific geometric property: if the plane containing the discontinuity also contains the origin, then $\mathbf{B}$ and $\mathbf{n}$ are perpendicular, and the boundary is a TD. If it does not include the origin, then $\mathbf{B}$ and $\mathbf{n}$ are not perpendicular and the boundary is a RD. In this sense, determining how close the plane is to the origin is equivalent to specifying the nature of the boundary. This property is emphasized by the two ideal boundaries, thus without fluctuations, which are represented in Figure 2.12.

The new methodology I propose to determine the nature of the boundary is as follows:

- First, I perform a careful inspection of the orbit in 3D.
- I compute both the MVA and SVD to obtain the two planes.

- Then, I visually identify the best estimate of the plane. This includes a rotation of the structure in 3D to get the best representative view of the hodograms. I consider the boundary normal to be well determined when at least one method gives a plane that includes the arc.
- Sometimes, both methods agree and the two planes overlap. In that situation, the following steps are performed using the [SVD](#) plane. This is usually the case for switchbacks with large deflections. However, in most cases, the methods do not agree.
- If the plane is too difficult to identify, then I discard the event for lack of clear evidence.
- When the plane of the discontinuity is clearly identified, I then consider if it includes the origin to determine the nature of the boundary.
- When the plane containing the arc-shaped structure contains the origin, I rely only on the [SVD](#) method. Its solution does not necessarily give a normal that is exactly perpendicular to $\mathbf{B}$ because of the wave activity.
- On the other hand, if the plane does not include the origin, then I estimate the normal using [MVA](#) and check the result visually.

I now have a combination of tools that gives a better insight into the topological properties of the orbit and should allow one to correctly determine the normal to the switchback boundaries.

The geometric properties and the visual identification are strong constraints in the identification of the plane. Thus, as they do not rely on the eigenvalues ratio nor the time interval used for the mean magnetic field determination, there is no need to discuss these values to interpret the results. This procedure, as such, cannot be automated because it requires human supervision.

2.4 Results

This section presents the main results of this work. Some were presented in the peer-reviewed article [Bizien et al. \[2023\]](#), which includes mainly the boundary nature and its thickness. I include a follow-up study of the boundary orientation and velocity jump. A second set of boundaries is studied here from a subsequent encounter.

Three distinct parts are presented here to analyze the nature of the switchback boundaries and should be distinguished from each other. A first discussion of the results based on the direction of the normal retrieved from the methodology is presented in Section 2.4.1. That corresponds to the geometrical identification of the nature of the boundary. The nature of the boundaries is also distinguished by their properties in the velocity field, which allows validation of the newly implemented methodology. As I present a new geometrical consideration, it is necessary to consider all aspects of the

boundary and investigate the velocity field of the switchback boundaries, presented in Section 2.4.2. The next step is to compare these results to earlier switchback boundaries studies. This is usually performed in the literature using a classification scheme presented in Sections 2.4.3 and 2.4.4. This scheme is then discussed in Section 2.4.5, as, by construction, most discontinuities fall into the unclassified category. The nature of the boundaries is then related to the open questions about the switchbacks, with the consideration of the boundaries properties that could highlight the mechanisms responsible for their evolution (Sections 2.4.7 and 2.4.8).

2.4.1 Orientation of the normal

Out of the 250 boundaries included in this study, 186 (74 %) are correctly classified by the methodology that I introduced previously. 179 switchback boundaries (71 %) are located in a plane that includes the origin of the sphere of constant $|\mathbf{B}|$. These correspond to TDs. In contrast, seven boundaries (3%) have a plane that clearly does not include the origin, which are then classified as RDs. The remaining 64 (26 %) are in between. The latter generally corresponds to switchbacks with small deflections whose boundary is blurred by wave activity and turbulence. In that case, neither of the two implemented techniques finds the plane of discontinuity.

A comparison between the two sides of the switchbacks is performed when both sides are correctly identified by my method. 78 switchbacks are studied (I then excluded 30 boundaries from the numbers stated before) and presented the analysis in Fig. 2.15. For most of the switchbacks, the leading and trailing rotations occur in the same plane. For a few events, the two planes are not parallel but present a significant angle between their relative normals. These cases correspond to smaller deflections from the Parker spiral, less than 90° .

One could investigate a potential preferential direction for the boundary plane compared to the Parker spiral. Figure 2.16 presents the investigation on the boundaries included in this study, with the angle between the Parker spiral and the boundary normal. A maximum angle is observed around 100° for the TD boundaries, which corresponds to a boundary plane almost parallel to the Parker spiral. This would be in adequation with the idea of switchbacks as a flux tube aligned with the Parker spiral [Laker et al., 2021]. The number of RDs is too small to interpret a statistical analysis. There is no clear dependence on the magnitude of the deflection from the Parker spiral. It would indicate that the general geometry is preserved for all angles of deflections. That should constrain the models that simulate the propagation of perturbations with boundaries that always preserve the orientation to the Parker spiral. Although the switchbacks appear to have a preferential deflection direction in the +T direction (from the RTN frame) [Fargette et al., 2022], the boundary plane is parallel to the Parker spiral direction. That gives more constraint to the understanding of the 3D geometry of switchbacks. These constraints will be discussed in Chapter 4.

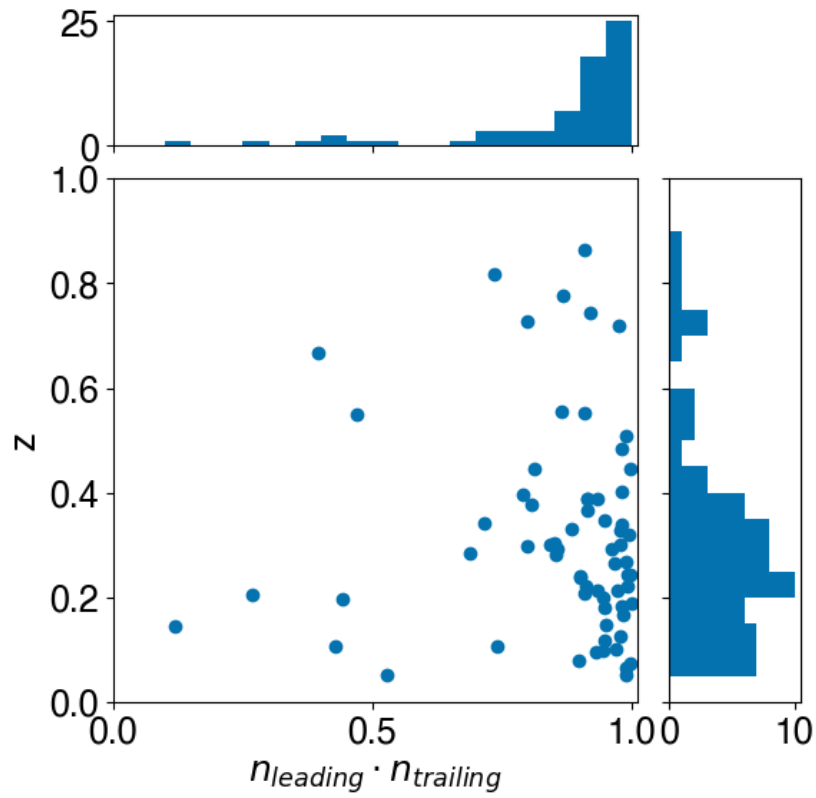


Figure 2.15: Scalar product between the leading and trailing normal as a function of the magnitude of the deflection from the Parker spiral.

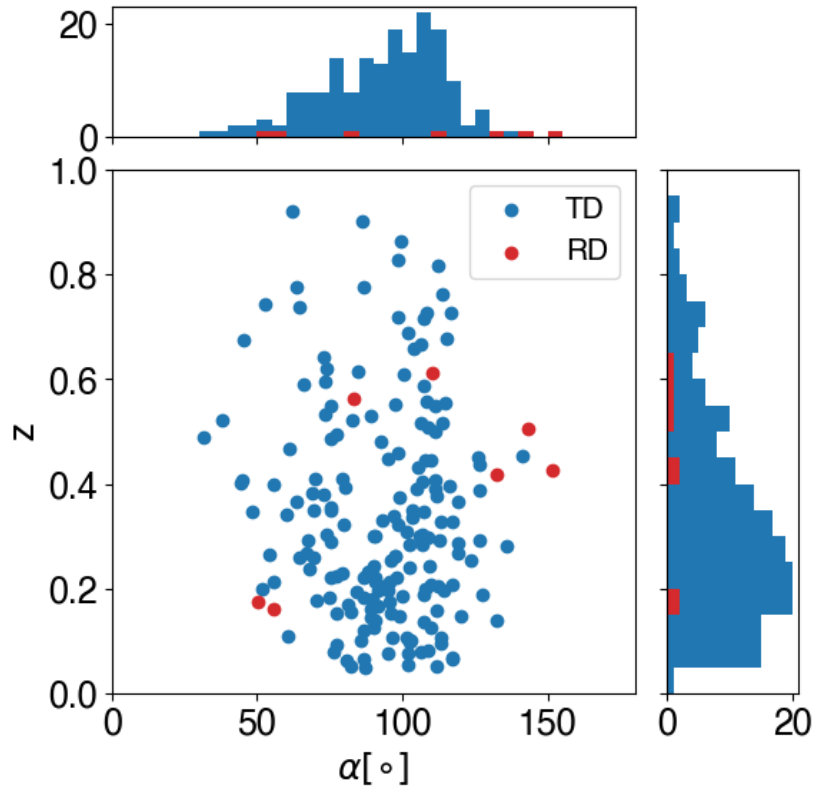


Figure 2.16: Angle α between the boundary normal and the Parker spiral direction as a function of the magnitude of the deflection from the Parker spiral.

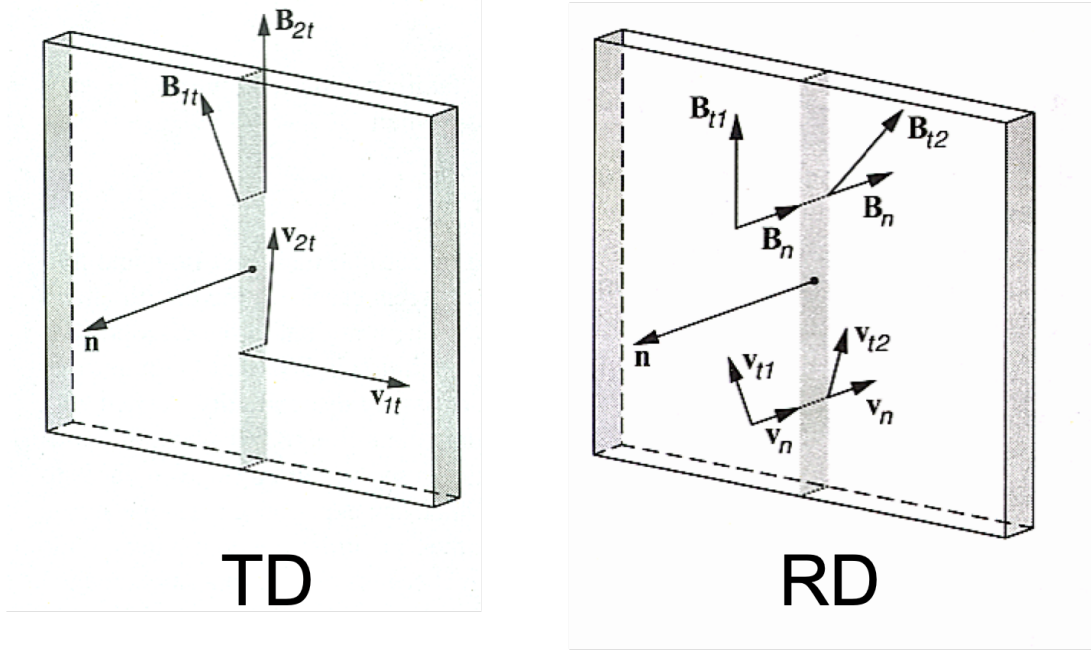


Figure 2.17: Illustration of the normal and tangential component of the magnetic field and velocity across a TD (left) and RD (right). Adapted from [Baumjohann and Treumann \[2012\]](#).

2.4.2 Velocity field constraints

As discussed in Section 2.1, the main properties to distinguish TD from RD are based on magnetic field measurements. However, the RDs also present some properties in the velocity field, and more precisely on the velocity jumps at the boundary. A necessary condition for having RDs is a large value of the ratio R_{VB} between the change across the boundary in the tangential component of the velocity v_t and that of the magnetic field B_t [[Baumjohann and Treumann, 2012](#)].

$$R_{VB} = \sqrt{\mu_0 \rho} \frac{[v_t]}{[B_t]}, \quad (2.15)$$

where ρ is the proton density at the discontinuity. The closer the ratio is to 1, the more likely a RD is identified, showing the correlated changes between the tangential components of the velocity and the magnetic field. In contrast, the ratio can have any value for TDs, which is expected to be closer to 0. An illustration of the geometry is shown in Figure 2.17, with the normal and tangential component of the magnetic field and velocity vector for an ideal TD and an ideal RD.

I calculate this ratio on a subset of 42 discontinuities identified as TD with the implemented methodology, which presents enough and good velocity measurements. This results in a broad distribution of ratios, presented in Figure 2.18, with 85% of the ratios with values lower than 0.2, thus clearly excluding the possibility of having RDs.

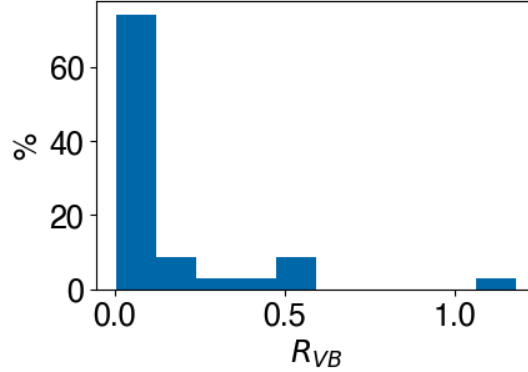


Figure 2.18: Histogram of the ratio R_{VB} between the change across the boundary in the tangential component of the velocity v_t and that of the magnetic field B_t .

In addition, the Alfvénicity can be investigated at the boundary, with the jump of v_t , normalized with the local V_A and the jump in B_t , normalized by the magnetic field magnitude $|\mathbf{B}|$. Figure 2.19 shows the two parameters computed for 42 boundaries with sufficient velocity measurements to estimate the jump. The dataset is smaller than the total number of boundaries studied but covers the full range of deflection angles. There is no correlation, with a Pearson’s coefficient of 0.18, not significant. That contradicts the hypotheses of a RD as we would expect a high correlation for RDs.

However, this figure allows us to discuss the relation between the propagation velocity of the switchbacks and the deflection angle. In this case, Pearson’s correlation coefficient between $\Delta v_t/V_A$ and z is 0.72, statistically significant. The boundaries appear to validate the relation presented in Matteini et al. [2014], stating that the jump in the velocity field is limited by the Alfvén velocity. That is due to the Alfvénicity of the structures that constrains the maximal magnetic fluctuation in the tangential direction to $2|\mathbf{B}|$. That would be the situation encountered for full reversals, in which case the velocity jump would be of $2V_A$.

Taken together, these different results all point to the tangential rather than rotational nature of the discontinuities. Let us now compare these results to those obtained in other studies. For that purpose, we introduce a classification scheme that is widely used in the classification of plasma discontinuities and is not only limited to switchback boundaries.

2.4.3 Classical boundary classification

First, I would like to state that this section refers to discontinuities that are not switchback boundaries. It is necessary to step aside this thesis context to introduce a classical scheme, and I will not then compare the numbers presented here with the classification I obtained previously. Now, I investigate the nature of each boundary by using the classical single-spacecraft classification scheme for boundaries [Smith, 1973]. This scheme relies on two quantities: the degree of collinearity $(\mathbf{B}/|\mathbf{B}|) \cdot \mathbf{n}$, and the change

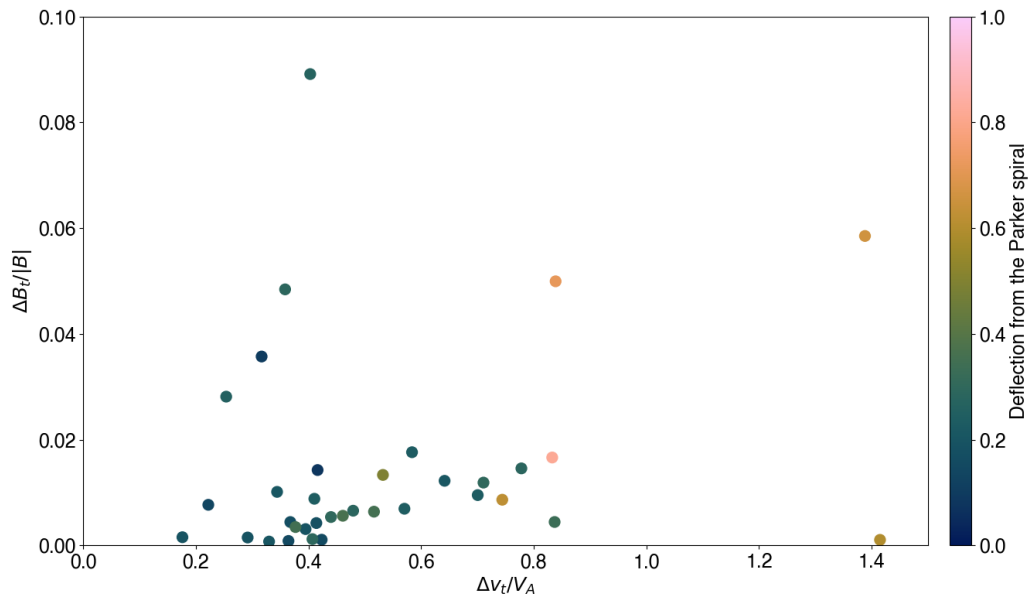


Figure 2.19: Jump in the tangential velocity v_t normalized to the local V_A compared to the jump in the tangential magnetic field component B_t normalized to the magnetic field magnitude $|\mathbf{B}|$. 35 boundaries were selected with sufficient velocity measurements to estimate the jump. The color code represents the normalized magnitude z of the deflection from the Parker spiral (Equation 2.8).

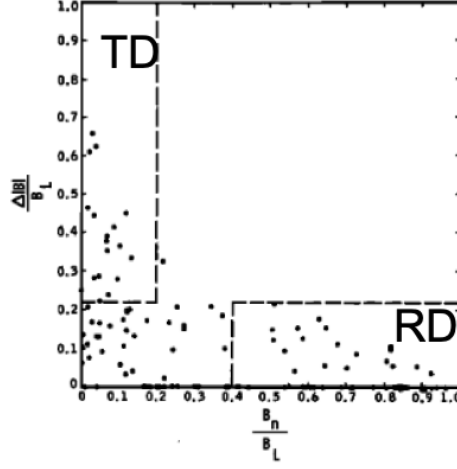


Figure 2.20: Classification of discontinuities, the relative jump in magnetic field magnitude with the normal component of the field. Reproduced from [Smith \[1973\]](#).

in field magnitude across the boundary $\Delta|\mathbf{B}|/|\mathbf{B}|$. [Smith \[1973\]](#) used a phase diagram to distinguish the two types of discontinuity, relying on the in situ measurements of discontinuities measured by Mariner 5. They find that a limit of 0.4 for $(\mathbf{B}/|\mathbf{B}|) \cdot \mathbf{n}$ and 0.22 for $\Delta|\mathbf{B}|/|\mathbf{B}|$ are classifying the TDs and RDs in their database. The limits for the parameters are based on empirical conditions with the best fit to their measurements. However, that excludes a certain number of discontinuities from being identified. In fact, in the discontinuity phase diagram presented in Figure 2.20, a certain number of discontinuities do not correspond to the classified discontinuities. They do not present the properties that allow us to distinguish clear TD from clear RD in the lower left side of the diagram.

[Neugebauer et al. \[1984\]](#) adopted a threshold value of 0.4 for the normal component of the magnetic field and 0.2 for the jump of magnetic field magnitude to clearly distinguish TDs from RDs. They also define two other categories, the Neithers (NDs), which are inconsistent with MHD discontinuities, and the Either Discontinuity (ED)s, which are not possible to be distinguished from TD or RD. The thresholds are summarized as:

<i>Rotational</i> (RDs) :	$(\mathbf{B}/ \mathbf{B}) \cdot \mathbf{n} \geq 0.4;$	$\Delta \mathbf{B} / \mathbf{B} < 0.2$
<i>Tangential</i> (TDs) :	$(\mathbf{B}/ \mathbf{B}) \cdot \mathbf{n} < 0.4;$	$\Delta \mathbf{B} / \mathbf{B} \geq 0.2$
“Either”(EDs) :	$(\mathbf{B}/ \mathbf{B}) \cdot \mathbf{n} < 0.4;$	$\Delta \mathbf{B} / \mathbf{B} < 0.2$
“Neither”(NDs) :	$(\mathbf{B}/ \mathbf{B}) \cdot \mathbf{n} \geq 0.4;$	$\Delta \mathbf{B} / \mathbf{B} \geq 0.2$

These criteria are still widely used today in the literature [[Tsurutani et al., 1996](#); [Horbury et al., 2001](#)]. Note that a high collinearity between $\mathbf{B}$ and $\mathbf{n}$ would provide unambiguous evidence for an RD whereas small values can imply either TDs or RDs [[Knetter, 2005](#)].

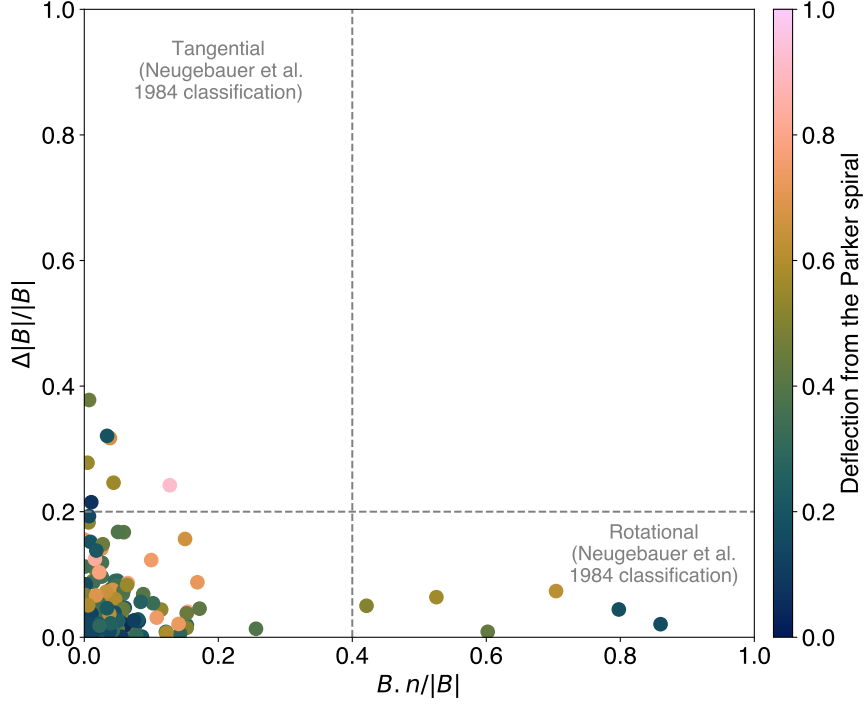


Figure 2.21: Boundary analysis using the classical classification scheme by [Neugebauer et al. \[1984\]](#). The normalized projection of the magnetic field along the normal $(\mathbf{B}/|\mathbf{B}|) \cdot \mathbf{n}$ is plotted against the variation of the magnetic field magnitude across the discontinuity $\Delta|\mathbf{B}|/|\mathbf{B}|$. The dashed lines divide the plane into four quadrants: TDs occur in the upper left quadrant and RDs in the lower right one. The remaining quadrants correspond to unclassified events. The color code represents the normalized magnitude z of the deflection from the Parker spiral (Equation 2.8). 186 boundaries are shown, excluding the 64 ambiguous cases. Reproduced from [Bizien et al. \[2023\]](#).

Now, let us move back to my switchback analysis and characterize the boundaries by means of this scheme. Figure 2.21 shows how the switchback boundaries are distributed, using the two-parameter classification scheme of [Neugebauer et al. \[1984\]](#). I only show those boundaries for which the normal can be clearly identified with the methodology, i.e., 186 cases out of 250.

I find that few boundaries would qualify as pure TDs or RDs. In the scheme introduced in this section, most boundaries belong to the so-called limit category with $(\mathbf{B}/|\mathbf{B}|) \cdot \mathbf{n} \rightarrow 0$, for which TDs and RDs cannot be distinguished based only on magnetic field data. I previously examined the necessary conditions for having perfect RDs or TDs. For classical TDs, we expect an arbitrarily large jump in the magnitude of the magnetic field. However, this is not a necessary condition in our context: when the structures are Alfvénic, and the change in the magnetic field at their boundary is modest, the jump can be arbitrarily small, while the discontinuity still remains a TD. This is precisely the case for switchbacks, which are known to be highly Alfvénic

[Kasper et al., 2019; Laker et al., 2022]. The boundaries located in the lower left corner of Figure 2.21 are therefore more likely to be TDs because of the small value of $(\mathbf{B}/|\mathbf{B}|) \cdot \mathbf{n}$, although the relative change in $|\mathbf{B}|$ is smaller than what is usually encountered with (mostly non-Alfvénic) discontinuities. Only multipoint measurements could help us fully resolve this ambiguity. The velocity measurements introduced in Section 2.4.2 allowed us to provide more constraints on these boundaries, confirming their TD nature.

2.4.4 Earlier switchback boundary studies

Although this work proposes a new methodology, it is not the first to focus on the nature of switchback boundaries. Previous studies present a statistical analysis of the boundaries, mostly on the first encounter of PSP. That encourages comparison of the results, as the population of switchback boundaries investigated should be similar in properties. Larosa et al. [2021] shows that there is no typical nature of the subset of switchbacks that they studied during the first PSP encounter. In fact, they found that RDs are slightly more common than TDs, but there is no definite tendency for one category. Akhavan-Tafti et al. [2021] argued that 78% of the boundaries are RDs by repeating exactly the same analysis on the same encounter. Figure 2.22 clearly shows that both studies find numerous boundaries in the ED section. Interestingly, they find few boundaries in the Neither Discontinuity (ND) section, which are not possible in theory. Both studies show that there are more strict RDs than strict TDs at the boundary of the switchbacks, without taking into consideration the ED. Akhavan-Tafti et al. [2021] find that there is no clear influence of the distance of the switchback to the Sun, visible with the colored dots in Figure 2.22.

However, Akhavan-Tafti et al. [2022] extend the switchbacks study to the first eight encounters and find that the ratio RD-to-TD seems to decay with the radial distance to the Sun. They propose that the RD may relax into TD as they propagate away from the Sun and potentially cause the heating and/or acceleration of the solar corona.

I argue that we should step back from their conclusions. In fact, the three analyzes used the same method to identify the normal, namely the MVA. The number of misidentified normals should be consequent, with a large overestimation of the collinearity of the magnetic field with the normal. That results in the conclusion of the omnipresence of RD observed in their results.

2.4.5 Critical comparison

We now know that these earlier studies most likely overestimated the number of RDs because of the automatic application of the MVA. However, they focused on events that appear to be correctly identified by the MVA, if one considers only the eigenvalues criterion. It is difficult to state that all the boundaries they classified were misinterpreted. Their results may include normal correctly identified by the MVA. That still does not validate the use of MVA only for such analysis. One could be tempted to say that the cases that were correctly identified are the one classified as ED by previous

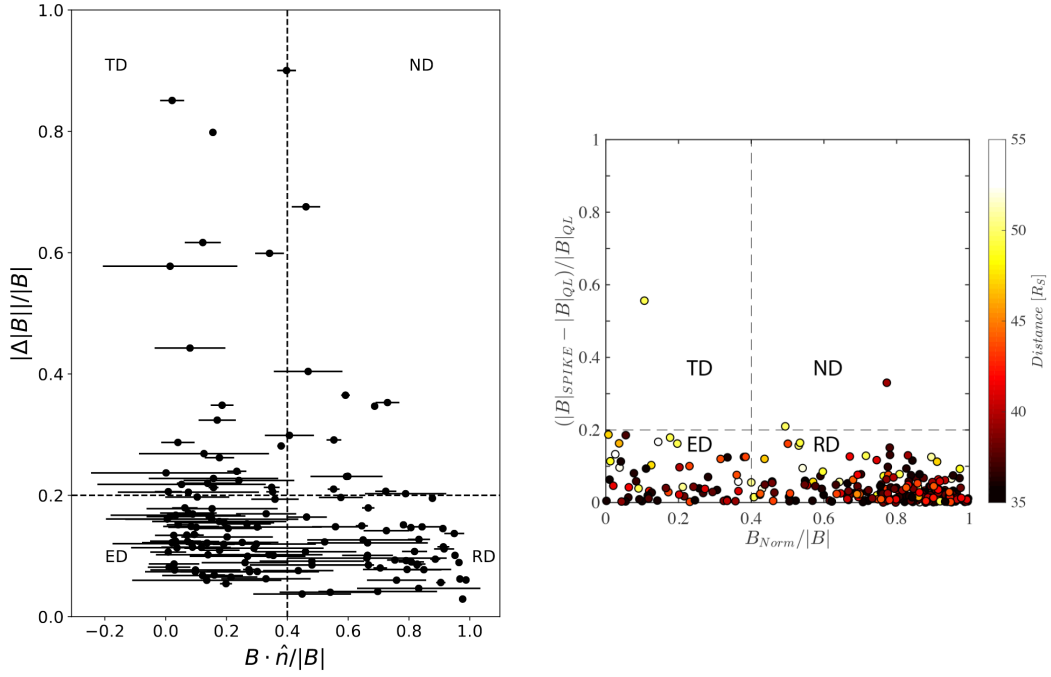


Figure 2.22: Classification scheme of switchback boundaries from E01, using the criterion from Neugebauer et al. [1984]. While both panels use different notations, the parameters are the same. Left: Reproduced from Larosa et al. [2021]. Right: The dependence on the distance to the Sun is color-coded. Reproduced from Akhavan-Tafti et al. [2021].

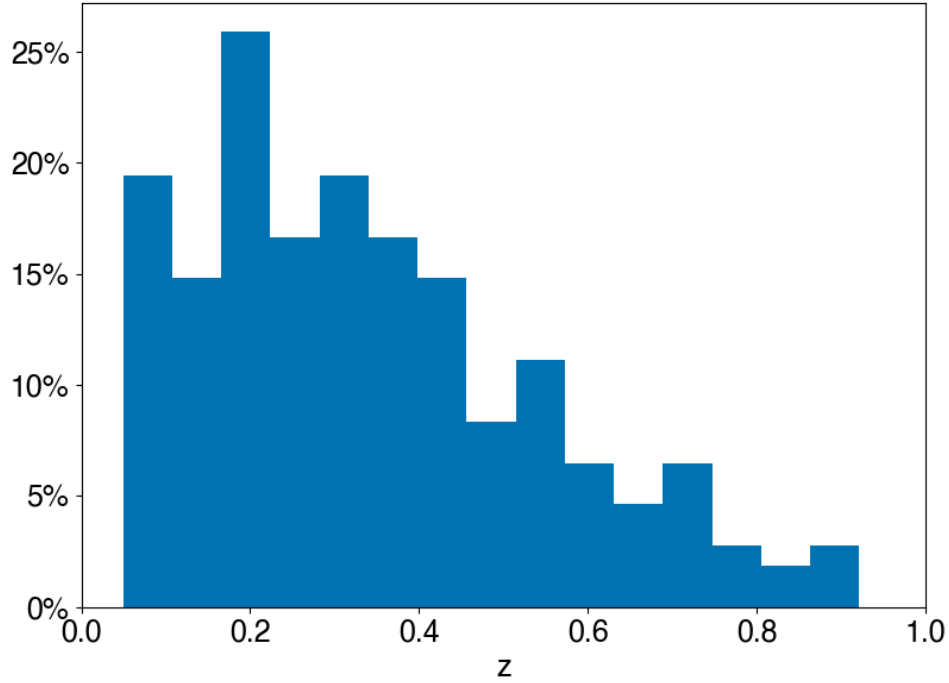


Figure 2.23: Histogram of the normalized deflection parameter z of the boundaries addressed in this study.

studies. In fact, for the cases identified by the [MVA](#), which are also identified by the [SVD](#), the plane includes the origin and the $(\mathbf{B}/|\mathbf{B}|) \cdot \mathbf{n}$ is small. As these situations were found for some of the boundaries that I studied, it is likely that some of the [ED](#) in Figure 2.22 are correctly identified. However, it would be difficult here to find the real [RDs](#).

Another critical aspect would be the database of switchbacks included in the different works. [Larosa et al. \[2021\]](#) identified manually switchbacks in the data, while [Akhavan-Tafti et al. \[2021\]](#) applied an automatic detection based on the shape of the structures, which excluded small deflections. It may result in different conclusions than the one presented in this chapter. However, in my analysis, the range of deflections starts from small angles about 36° to large deflections, as presented in Figure 2.23 the distribution of the deflections included in this analysis. The largest deflections, with angles above 90° , would definitely be included in the previous studies. These deflections are categorized as [TDs](#) in my analysis. Thus, the database is representative and cannot explain the differences between the results of this chapter and previous studies. Moreover, the analysis of the influence of the deflection does not show any correlation between the nature and the deflection angle, as observed in Figure 2.21. This will be discussed further in Section 2.4.7.

I show that most discontinuities are then much closer to tangential, and therefore the switchback boundary is more impermeable to plasma flow than expected. This has important implications for the rate at which switchbacks can erode in the solar wind, as I will discuss in the following section.

The results I find show similar tendencies as the estimation from triangulation of discontinuities in the solar wind. Most $(\mathbf{B}/|\mathbf{B}|) \cdot \mathbf{n}$ are small [Horbury et al., 2001]. Using three spacecraft, mostly TD and ED are found [Burlaga and Ness, 1969; Horbury et al., 2001]. Knetter et al. [2003, 2004] used 4 point measurements with Cluster. They statistically compared the result of the triangulation with the MVA applied at each spacecraft. They found that all the discontinuities identified as RDs with the MVA should be identified as EDs when identified with the triangulation normal. One could wonder if the structures they investigated are Alfvénic structures that could be similar in properties to the switchback boundaries. They did not include a velocity analysis so we cannot conclude on the correlated fluctuations. However, the magnitude of the field was conserved, which could indicate an Alfvénic nature.

2.4.6 Multiple encounters comparison

Until now, the study presented mostly focuses on the results presented in the publication Bizien et al. [2023]. However, the work should be extended to boundaries from other PSP encounters. That would indeed allow us to study the evolution of the nature of the boundaries with radial distance to the Sun. That was the objective of a side project performed with a master student of the University of Orléans, Tristan Vergé. He worked on the first encounter first to train on the boundary estimation. He analyzed the same dataset of switchbacks than the one I have investigated. That allowed me to estimate the impact of a different selection of the interval on the results. Interestingly, he analyzed a second population of boundaries, from a latter encounter, closer to the Sun at $13 R_{\odot}$. He selected 52 boundaries from E10, using the tool I developed, which is convenient for allowing multiple users to perform the analysis. We discussed the greater difficulty in identifying boundaries compared to E01. In fact, the boundaries are less defined, as the deflection is less sharp. They also included more substructures. Applying the same methodology to the boundaries, I found that most are TDs, about 71 %, few are RDs, about 6 %, and a large portion are not classified, about 23 %. To allow for comparison, I show the boundaries in the classical classification scheme in Figure 2.24. I can draw similar conclusions as for the previous results, as most boundaries are in the ED section.

These results still challenge the work of Akhavan-Tafti et al. [2022], about the evolution of boundaries at different distances to the Sun. Here, I find that even at closer distances to the Sun, most boundaries are TD. The question of the representative aspect of these results arises. In fact, only 26 switchbacks were considered here. They are spread on radial distances from 15 to $40 R_{\odot}$, which covers a large interval to allow to conclude on the radial evolution. However, this data set of boundaries, combined with the cases of E01, does not allow to conclude on the existence of the few RD. A

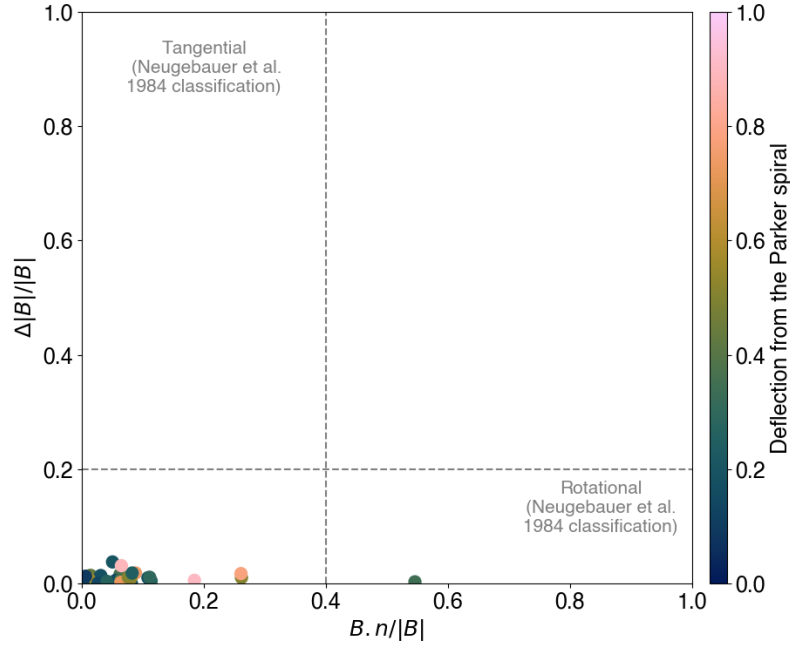


Figure 2.24: Same as Figure 2.21 but for 52 boundaries identified in E10 data.

larger dataset of boundaries from different encounters with different plasma conditions could be necessary to investigate the low occurrence of RDs.

2.4.7 Self-similar properties

The nature of the boundaries is important for the survival and propagation of the structures. It is also clear that switchbacks show a large range of deflection angles, which appear to have an influence on the modulation we observe in the time-series. In fact, the time-series that cover a full encounter show an interval with larger deflections and intervals with smaller deflections, which are referred to as patches in the literature [Bale et al., 2021]. It is then of interest to consider the influence of the magnitude of the deflection on the nature of the boundary. Figure 2.21 includes deflections of all magnitudes, including full reversal switchbacks (for which $z > 0.5$). Interestingly, the type of discontinuity does not depend on the magnitude of the deflection: small deflections behave similarly to large deflections. This confirms earlier observations by Dudok de Wit et al. [2020] that these deflections are self-similar, with no characteristic cut-off beyond which they behave differently. This is true down to a value of approximately $z = 0.1$, below which it becomes increasingly difficult to distinguish switchback boundaries from random fluctuations. These results suggest that small deflections are unlikely to be the result of an erosion of large reversal structures. The opposite scenario is more difficult to analyze. In fact, large deflections can be the result of the expansion of small deflections. This hypothesis appears to be the theory implemented

in simulations that produce switchbacks [e.g., Wyper et al., 2022].

2.4.8 Thickness of the boundaries

A property that could highlight the mechanisms responsible for their evolution is the thickness of the boundary. One could imagine that they are the markers of evolution and would keep a signature of the possible erosion mechanisms. In theory, the thickness of the boundary is a property that can only be determined if one retrieves the normal to the boundary. In fact, the apparent duration in the time-series is not directly related to the physical dimension of the structures. It depends heavily on the angle of the crossing of the structure by the spacecraft and also on the spacecraft velocity, as presented in Chapter 1 for the full structure. However, it is possible to correct the estimation of the thickness from the influence of the crossing angle, using the orientation of the normals.

The above results show that we now have more realistic estimates of the switchback boundary normals. The thickness of the boundaries can then be inferred from the normal velocity of the protons and the duration of the boundaries in the MAG time-series. For some events, the proton velocity could not be used, so our sample contains 165 events out of the 186 classified boundaries. The classified boundaries correspond to those identified by the methodology.

I determine the thickness of each boundary from

$$D = (t_d - t_b) \cdot (\langle \mathbf{V}_{pl} \rangle - \mathbf{V}_{SC}), \quad (2.16)$$

where D is the thickness of the boundary, t_b and t_d the time in seconds of the beginning and end of the boundaries in the time-series, respectively; $\langle \mathbf{V}_{pl} \rangle$ is the mean plasma velocity outside the switchback and $\mathbf{V}_{SC}$ is the spacecraft velocity. Both velocities are in the RTN frame projected in the normal direction.

Theoretically, the propagation velocity of the discontinuity with respect to the spacecraft should be included in the calculation. Indeed, the plasma velocity considered in the computation is the bulk solar wind. However, the switchbacks have a relative velocity with the plasma frame. However, we cannot determine it with a single spacecraft, and so the estimation of the thickness relies on the assumption of the nature of the discontinuity to include or not the Alfvén velocity, for TDs and RDs, respectively [Knetter, 2005].

Figure 2.25 shows the thickness of the 165 boundaries as a function of the magnitude of the deflection from the Parker spiral. First, I find that most of the discontinuities have a thickness of about one order of magnitude over the local proton inertial length. The mean inertial length of the ion during the first encounter of PSP is 16km. The thickness ranges from the order of the local proton inertial length to two orders of magnitude higher. Secondly, I note that the distribution of thicknesses is a factor of 3-10 smaller than those found by Larosa et al. [2021]. This difference was to be expected because I provide better estimates of the normals, which are more perpendicular to $\mathbf{B}$ than the ones found by Larosa et al. [2021]. The number of RDs is too small to interpret a statistical analysis.

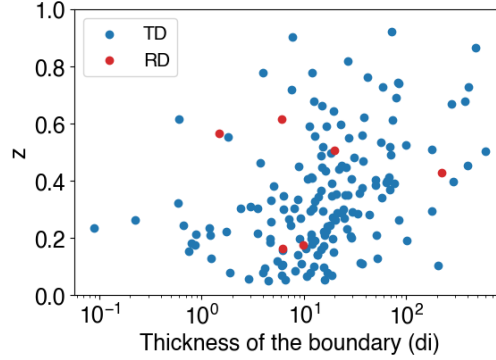


Figure 2.25: Boundary thickness as a function of the magnitude of their deflection from the Parker spiral. The thickness is expressed in units of the local proton inertial length. The mean proton inertial length over the first encounter of PSP is 16km. The TD are presented in blue, the RD in red.

The thickness of the boundaries can now be compared with the characteristic length of the local plasma. Interestingly, most of the thicknesses exceed the proton inertial length, so the boundaries can be considered as MHD discontinuities. I also find that the magnitude of the deflection has no effect on the thickness of the boundary. In fact, there is no dependence between the angle of deflection and the thickness of the boundary, with a Pearson’s correlation coefficient of 0,34 (statistically significant). No correlation is apparent, but there is, however, a region of exclusion, as large deflections do not have a thin boundary. One could expect that larger deflections would have thicker boundaries. This supports the self-similar geometry that I alluded to earlier, where all switchbacks belong to the same population of structures, regardless of the magnitude of their deflection. Interestingly, this also pleads for a common origin of all switchbacks.

Another result is that there is no clear correlation between the thickness and the type of boundary. However, the limited amount of RDs may not allow us to conclude on the statistical properties here.

Previous studies have shown that there is an asymmetry in the properties of the boundaries between the leading and trailing edges [Huang et al., 2023a]. In fact, in our study, there appears to be a difference in thickness between the leading and trailing edges when considering the same structures. There is no tendency for half of the structures to have a leading boundary larger than the trailing boundary. That discussion should, however, be linked to the position of the switchback on the orbit. No clear asymmetry is observed in the structures depending on their position during the first encounter, such as corotation times (in red on the figure) or longitudinal sweep, as illustrated in Figure 2.26. The position of each identified switchback is plotted on the spacecraft trajectory. The color-coded dots show the ratio of the leading boundary thickness to the trailing boundary thickness. One could expect that the leading boundary could be more compressed than the trailing boundary due to the propagation of

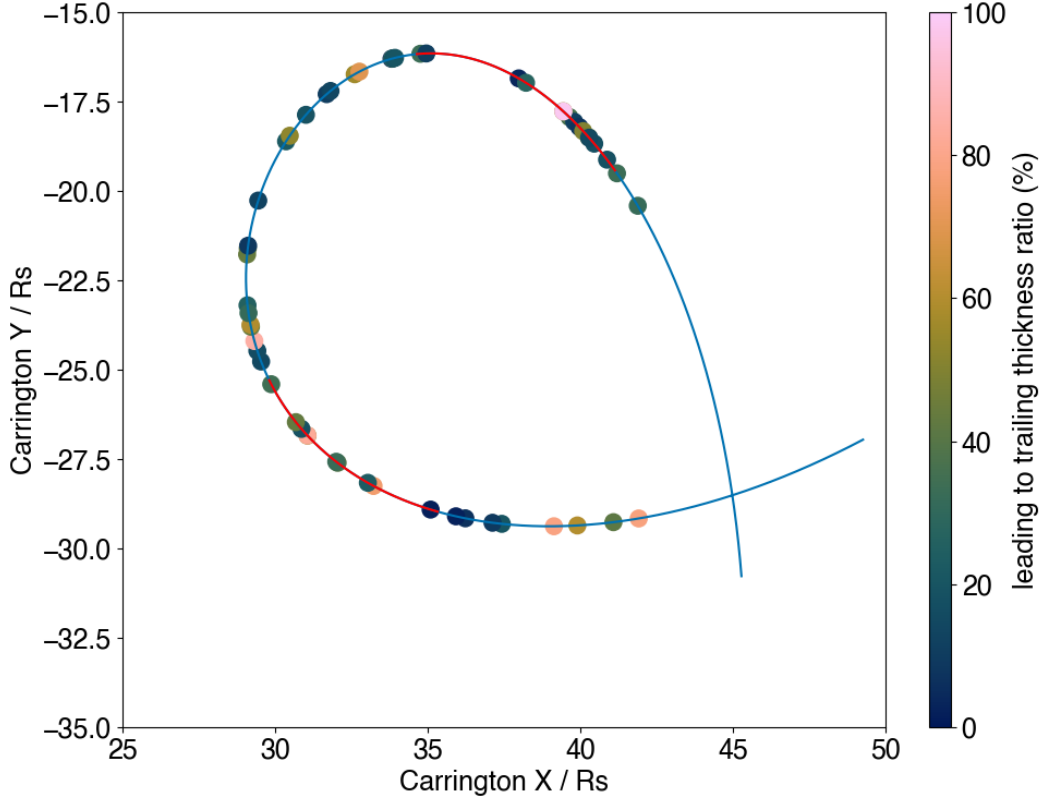


Figure 2.26: Evolution of the ratio between the leading boundary thickness to the trailing boundary thickness, depending on the position on the orbit. The red intervals correspond to the two corotating intervals of E01. 65 switchbacks are presented here with both boundary normals identified by the methodology.

the switchback in the slower background solar wind. This compression with a higher density at the leading edge is found in [Liu et al. \[2022a\]](#). This is, however, not observed in the boundaries of this study.

Figure 2.27 shows the investigation of a relation between the thickness of the boundaries as a function of their radial distance to the Sun. There is no clear relation between the thickness and the radial distance to the Sun, with a Pearson's correlation coefficient of 0.07 (statistically not significant). However, there is a region of exclusion, as thin boundaries are not observed at large distances. The interpretation of the absence of relation means that there is no apparent erosion of the boundary as the switchback propagates. However, this is a statistical interpretation, and I cannot contradict the hypothesis of an erosion of the structures.

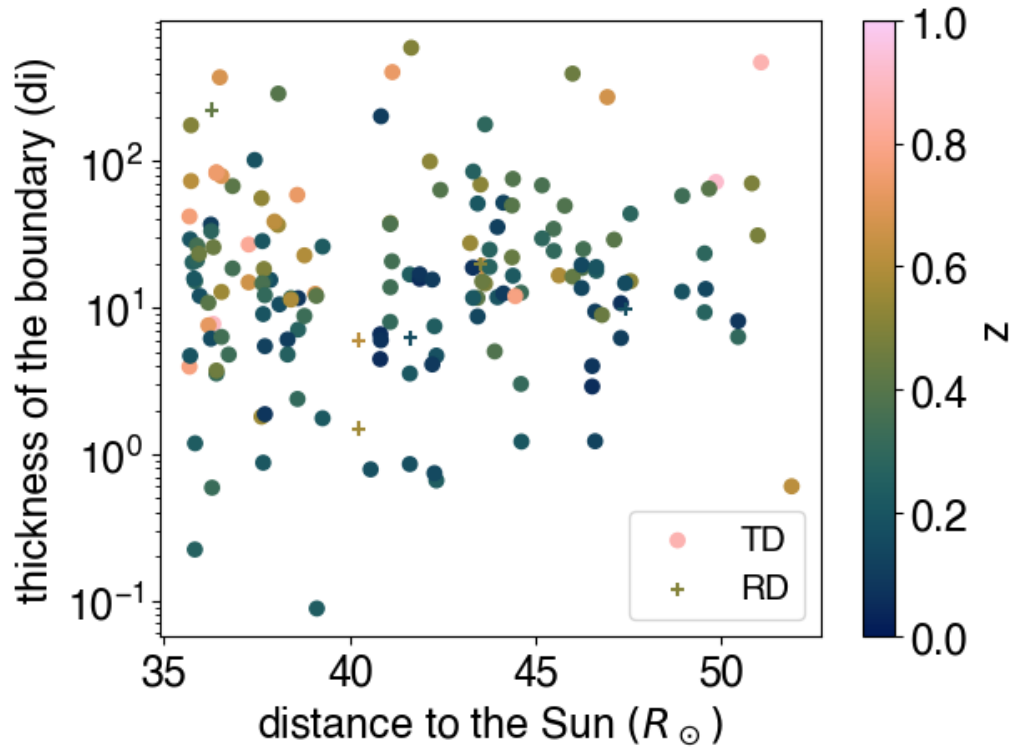


Figure 2.27: Thickness of the boundary, expressed in units of the local proton inertial length, as a function of its radial distance to the Sun, expressed in units of Solar radius. The colorbar indicates the normalized deflection angle. The RDs are presented with cross markers and the TDs with round markers.

2.5 Discussion

This work leads directly to a certain number of questions about the structures and the implications of the solar wind open questions:

- Nature of the boundary
 - What is the impact of the 3D geometry of the boundaries?
 - How can we relate the closed nature of the boundary with the Alfvénic properties of switchbacks?
 - Is there an influence on the magnitude of the deflection?
 - Does the deflection exhibit distinct types with unique properties, or is it a continuous spectrum of events?
- Propagation and evolution
 - Do switchbacks evolve during their propagation away from the Sun, and how?
 - Is the boundary subject to erosion, and is there a energy transfer?
 - Do these structures increase in magnitude as they propagate, or is their size predetermined at the point of origin?
- Origins of switchbacks
 - Where do they originate?
 - Can we reject certain origin theories based on these results?

The following sections attempt to answer these questions with the results presented above.

2.5.1 3D nature of the boundary

Most of the methodology and interpretation of the results applied in this work rely on the assumption that we work with planar structures, or at least structures that can be approximated as planes. However, one of the first discoveries of this work, which led to the new proposed methodology, is that the switchback boundaries are not like any type of discontinuities found in the solar wind. Indeed, they are Alfvénic, in the sense that they conserve the magnetic field magnitude. Thus, the rotation of the field vector during the boundary interval is located on the surface of a sphere. This enlarges the definition of the boundary, as we exit the domain of the planar waves and move to the spherical waves physics. This was already discussed in [Tsurutani et al. \[1997\]](#) and subsequent reviews [[Tsurutani and Ho, 1999](#); [Tsurutani et al., 2018](#)].

However, it appears that, indeed, even in the context of spherical waves, a planar structure can always be identified. These structures, the so-called arc-polarized

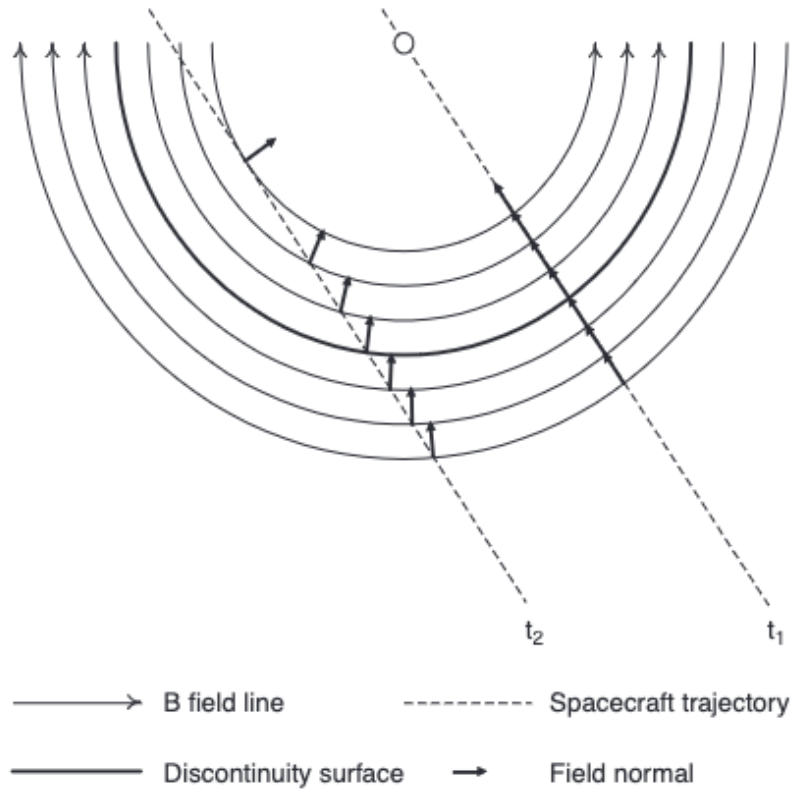


Figure 2.28: Illustration of the curvature of the boundary and its effect on the normal estimation. Reproduced from [Dunlop and Woodward \[1998\]](#).

waves, are well known and are studied in the solar wind by multiple missions, including multispacecraft missions (e.g., Cluster).

One could imagine that the boundaries are curved structures, and thus, any interpretation from single-point measurements should be considered carefully. Figure 2.28 shows the influence of the curvature of the discontinuity as well as the angle of the crossing and the location of this crossing compared to the curvature axis.

Despite consideration of the planarity of the boundary, the boundary is not necessarily completely flat. That cannot be identified by single spacecraft measurements, but one could consider the idea of a rippled front as presented in [Hanson et al. \[2019\]](#). This was performed with Magnetospheric Multiscale (MMS) on shocks.

Discussion arose from the complex 3D nature of the boundaries, in the idea of developing new tools to interpret the nature of the boundary without restricting to their planar nature. This is still in development, but some ideas rely on the use of the Möbius transform [[Brosius et al., 2024](#)]. The method is less constrained than the MVA and the SVD and allow retrieving the polarization through an ensemble of transformations from variations in parameter values.

2.5.2 Alfvénicity

In theory, RD are Alfvénic structures, with $[v]$ parallel to $[B/\rho]$, while this alignment is not required for TD. However, such an alignment may be observed in the case of the superposition of Alfvénic fluctuations on a boundary that is a TD. I analyzed the ratio R_{VB} for most boundaries. In the case of ideal RD, it is close to 1 and arbitrary for TD. However, in the solar wind, for most discontinuities as well as Alfvén waves, it is constantly less than 1 [Neugebauer, 2006]. This is also what I observed in the switchback boundaries that I analyzed in Section 2.4.2.

One could imagine that the Alfvénicity is lost at the boundary, while the complete structure remains mostly Alfvénic. This is observed for some boundaries with compressibility. Larosa et al. [2021] finds that 27% of their 70 cases show a deviation from the Alfvénicity with compression. That work is performed by comparing the magnitude of the field inside the structure with the magnitude of the ambient magnetic field. Magnetic field dropouts are also detected at the boundary so that the magnitude is not conserved [Farrell et al., 2020]. The field magnitude drops by approximately 8% for 33 switchbacks.

It could also be the signature of the merging of switchbacks [Agapitov et al., 2022]. The Alfvénicity may increase after subsequent merging until reaching a maximum. When the maximum is reached, the reconnection that allows the merging of switchbacks is blocked, and the merging stops. In that case, we may observe an evolution of the Alfvénicity with the evolution of the switchbacks.

2.5.3 Impact of closed boundaries

Our study clearly shows that the boundaries of switchbacks are closed. That prevails for most boundaries studied, without dependence on the deflection angle, the distance to the Sun, or the position on the orbit. That emphasizes the self-similar properties of the switchbacks. This is also directly related to the observations of switchbacks at larger distances. In fact, it suggests that stable boundaries prevent the structures from disappearing. The following discussion is related to the open questions about the heating and acceleration of the solar wind. In that case, the interpretation becomes more complex. How do stable structures that prevent plasma exchange heat and accelerate the solar wind? One hypothesis could be that I observe the most stable structures that are able to survive, propagating in the solar wind. Then, switchbacks with different properties, which may not be stable enough, would quickly disappear and mix in the solar wind. The dissipation of this population of unstable switchbacks could bring the energy to heat and accelerate the solar wind. However, there is no evidence of this hypothesis yet. The reasoning would lead to the interpretation that the few observed open boundaries would be a convenient candidate for the subpopulation of switchbacks that would disappear.

2.5.4 Propagation behavior

One striking question that could directly challenge our results is about the evolution of the structures in the solar wind. I state that the structures are TDs. However, TDs are advected by the solar wind, and they do not have relative velocity to the background plasma, as discussed in Section 2.1.2. In contrast, switchbacks and their boundaries are Alfvénic structures. The magnetic field fluctuations are correlated with the velocity fluctuations through the Alfvén velocity v_A . As the maximum δB is $2B_0$, the maximum δV is $2v_A$ [Woolley et al., 2020]. Interestingly, the propagation velocity of the switchbacks is then directly related to the deflection angle [Matteini et al., 2014].

So, we have advected structures at the boundary of propagating structures. One could imagine that such a situation would rapidly degenerate. This contradicts the numerous observations of switchbacks. Denskat and Burlaga [1977] mentioned the existence of static, non-propagating Alfvénic structures. That could be the interpretation of the boundaries of the switchbacks. The other possibility is that it is possible for the switchbacks with these properties to propagate. The last possibility is that they are not closed and stable boundaries, limited by the interpretation of the $(\mathbf{B}/|\mathbf{B}|) \cdot \mathbf{n}$. These aspects should be considered in future studies as it is still clear that switchbacks evolve as they propagate. The stable boundaries could then evolve through other processes, such as magnetic reconnection.

2.5.5 Reconnection at the boundary

Among the processes that could erode these boundaries is reconnection, which has been observed in a limited number of boundaries. Froment et al. [2021], for example, showed three switchbacks examples of boundaries with evidence of reconnection. The signature of reconnection is observed in an enhancement of velocity and a correlation of the velocity and magnetic fluctuations followed by an anticorrelation. These criteria correspond to the ion jets observed in the solar wind [Gosling et al., 2005]. However, we do not see a causal link between the few identified RDs and the few cases of reconnection at the switchback boundary. One could expect that RDs are favoring the reconnection while TDs prevent it. I analyzed the cases presented in Froment et al. [2021]. All of them were correctly identified by the methodology, with well-defined arcs. Interestingly, they show a small $(\mathbf{B}/|\mathbf{B}|) \cdot \mathbf{n}$ and would then be identified as TDs.

The number of identified reconnection cases at the boundary remains considerably low, with about 6 switchbacks (12 boundaries) for many encounters with the Sun of PSP and Solar Orbiter (SolO) [Froment et al., 2021; Suen et al., 2023]. The PSP reconnection cases all present the characteristics of TDs. I did not perform the analysis on the SolO cases. That also deserves some attention, as we would expect the boundaries allowing for reconnection events to be open boundaries with possible plasma flows.

If we step back from the discussion about the nature of the discontinuity and think about the impact of the switchback evolution, the question is now: What would be the implication of the absence of identified reconnection events? One could assume that the conditions for reconnection to occur are strict and rarely met at the boundaries

of switchbacks. Some other processes may prevent reconnection from being initiated, such as the large velocity shear at the boundary [Doss et al., 2016; Peery et al., 2024]. These velocity shears would be directly related to the Alfvénicity of the structures. Another possibility is that the reconnection occurs closer to the Sun, where it cannot be probed. However, there are not yet studies on the influence of reconnection on the switchbacks evolution.

2.5.6 Boundary waves and instabilities

An interesting aspect of the discontinuities is the investigation of their link with the disappearance of the switchbacks in the solar wind, which could then cause the energy to accelerate. In fact, this is the objective behind the investigation of the nature of the boundary. As discussed previously, the small number of reconnection events prevents drawing conclusions about the possible energy source from switchbacks at close distances to the Sun. However, other phenomena may play a role at the boundary, such as waves and instabilities. Waves have been observed at the boundaries of switchbacks. Malaspina et al. [2022] observed kinetic Alfvén waves, and Mozer et al. [2021b] reported the presence of ion-acoustic waves. Intense surface waves are reported that have large angles with respect to the normal to the surface, of more than 60° [Krasnoselskikh et al., 2020]. Larosa et al. [2021] detected an enhanced level of wave activity at the boundary, with some of them being surface waves. Farrell et al. [2021] reported on ultralow frequency (ULF) wave activity. It was also observed that bursts of low-frequency whistler wave packets are collocated with magnetic dips at the boundary of switchbacks, as the dips favor the production of whistlers [Agapitov et al., 2020]. Are the waves at the boundary a signature of the switchback erosion? Interestingly, the dips favor the generation of sunward-directed whistlers [Choi et al., 2024]. Indeed, when they are not specifically associated with dips at the boundaries of switchbacks, they propagate anti-sunward.

2.5.7 Any insight on the origin?

The nature of the boundaries brings more understanding of the propagation behavior of the switchbacks. Interestingly, the nature of the boundaries could also bring insights into the origin of the switchbacks. As I find more numerous TDs than RDs, the consequent survival of the structures during their outward propagation is compatible with an origin that is rooted in the solar atmosphere. Indeed, to survive at large distances, they need to be stable and less subject to the effects of the waves and instabilities discussed above. However, our results do not provide a sufficient condition for excluding the in situ generation of switchbacks. It is possible that they are indeed stable but can be generated in situ. Interestingly, the nature of the boundary could give more information about the origin of the structure. In Huang et al. [2023a], they discussed the formation of TD from the complex topology of the braided closed field [Janse et al., 2010], while RD would be generated from interchange reconnection [Lin et al., 2009]. The discussion about the generation of RD through interchange

reconnection is due to the small value of $(\mathbf{B}/|\mathbf{B}|) \cdot \mathbf{n}$, which also respects the Walén relation. Huang et al. [2023a] argued that the switchbacks formed from interchange reconnection should have a RD on the reconnection side, while the other side would be a TD. This is not observed in the cases that I have investigated, as both sides have the same nature. But I cannot exclude that this may be the case for the few RD found in the statistics. In my analysis, this is not observed.

2.6 Chapter conclusions

In conclusion, I have investigated different methods for studying the boundary of magnetic switchbacks as observed by PSP during its first solar encounter. I find that these boundaries have a very specific geometrical shape since all are arc-polarized structures whose rotation occurs on a sphere, but it is also contained in a plane. For that reason, they have a very specific topology as they are 1D structures.

My findings also caution against the routine use of MVA for identifying the nature of the boundaries of structures that are highly Alfvénic, regardless of the ratio of its eigenvalues. The presence of fluctuations often causes the method to wrongly identify boundary normals that are collinear with the magnetic field. Thus, it has a bias toward boundaries that appear to be rotational. The review of the flaws of MVA has been extensively done in the literature, while it is still used in new switchback studies. Thus, a rigorous methodology is proposed to identify the nature of the switchback boundaries by a better estimation of the normal.

A large majority (71%) of these planes include the origin. This specific geometry implies that the normal is mostly perpendicular to the magnetic field, which then implies that they are tangential discontinuities. Very few (3%) of the planes do not include the origin and thus qualify as rotational discontinuities. The remainder (23%) is unclassified due to the lack of clear orientation of the normal. These numbers were obtained during the first encounter of PSP with a relatively large radial distance at $R_{\odot}$, but similar proportions are found in a later encounter in which the closest distance to the Sun is $13.3R_{\odot}$. Our analysis further reveals no clear influence of the magnitude of the deflection from the Parker spiral on the type of boundary nor their thickness, confirming the self-similar nature of switchbacks.

However, I cannot provide definitive proof of the nature of these discontinuities, as the structures are too complex to fall into the simple scheme implemented before. There is considerable evidence to suggest that most of them are not rotational and, therefore, tangential. This conclusion is in contrast to previous analyzes that found a predominance of rotational discontinuities highly related to the use of MVA. In turn, it suggests that the switchback boundaries are more likely to be closed. These conclusions raise another aspect that should be considered in future studies. A tangential discontinuity does not have a velocity relative to the plasma, so it does not propagate in the solar wind. Thus, the absence of relative velocity of the boundary should not influence the switchback crossing. This is contradicted by some of the observations which show noticeable velocity spikes.

Considering the questions raised by the present analysis, presented in Section 2.5, some can be discussed with regard to the results presented, and others are still unanswered. The last category is, however constrained by the results and opens the path to future investigations:

- Nature of the boundary
 - What is the impact of the 3D geometry of the boundaries? The arc-shaped structure of the boundary is highly impacting the methodology implemented. However, it is not clear why such type of structure is bounded to the magnetic reversals. It highlights the need for 3D analyses of boundaries that are not restricted to a planar assumption.
 - How can we relate the closed nature of the boundary with the Alfvénic properties of switchbacks? The Alfvénicity of the switchbacks is observed at the boundary with the rotation of the field vector on the surface of a sphere of radius the magnitude of the field. However, the Alfvénicity appears to be lost at the boundary with the tangential nature of the boundary and the absence of characteristic correlation in the velocity and magnetic field.
 - Is there an influence on the magnitude of the deflection? The switchback boundaries show similar self-similar properties as the reported properties of switchbacks.
 - Does the deflection exhibit distinct types with unique properties, or is it a continuous spectrum of events? The boundaries generally show properties of Tangential Discontinuities, while the origin and existence of Rotational Discontinuities are unexplained. A hypothesis could be about the different origins of both types of boundaries but does not prevent the hypothesis of a Rotational boundary that would evolve into a Tangential boundary.
- Propagation and evolution
 - Do switchbacks evolve during their propagation away from the Sun, and how? The boundary nature does not show an evolution with the radial distance, but it is not possible to conclude on the evolution as there is no proof that closer to the Sun, more RD could be observed.
 - Is the boundary subject to erosion, and is there a transfer of energy? This question could be linked to the nature of the boundaries, as the stable TD are less likely to be eroded. A possible erosion mechanism is magnetic reconnection at the boundary, but there is only a limited number of studies on this local phenomenon to understand how reconnection would erode the boundary.
 - Do these structures increase in magnitude as they propagate, or is their size predetermined at the point of origin? The question can be answered specifically for the boundaries, as there is no apparent increase in the thickness

of the boundary with the radial distance to the Sun, but there is an area of exclusion as large deflections do not have a thin boundary.

- Origins of switchbacks
 - Where do they originate? The results are compatible with an origin rooted in the lower solar atmosphere.
 - Are we able to reject certain origin theories based on these results? We cannot exclude the in situ generation from the results obtained in this thesis. This question would require investigation of a solar source to exclude the solar origin or to find a physical explanation for all the in situ properties of switchbacks in the in situ generation theories, such as the self-similarity.

Taken together, the results presented in this chapter challenge the classical picture of switchbacks and suggest that their erosion could be much slower than expected. Switchbacks, with their stable boundaries, could survive longer as they propagate out into the solar wind. This encourages a study of the probable solar origin of the switchbacks, which will be performed in the following chapter.

Switchback origin

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3.1 Introduction

In Chapter 2, we showed that the switchback boundaries behave as tangential discontinuities and are, therefore, closed. This, in turn, suggests that they are stable structures that can survive during their propagation in the solar wind. These results are also compatible with an origin of switchbacks in the lower solar atmosphere, which motivates the second part of my thesis. In this chapter we aim at providing a new estimation of the solar precursors of the switchbacks, using in situ measurements and remote sensing observations of the source region, an approach that remains largely unexplored. This chapter includes results that are published in *Astronomy and Astrophysics*. The cases I considered in the paper are the only ones that showed an unambiguous connection between the spacecraft and the solar source region and that allowed a clear identification of small-scale eruptive events. This chapter provides a more general presentation of all the cases I considered in the paper and the challenges I encountered during this complex data analysis. I will also discuss some strategies that could be applied.

3.1.1 Motivation

One of the main open questions about switchbacks is about their origin. The large majority of studies are solely based on in situ observations. However, their origin is still subject to major debates as there is no definite proof of any of the theories put forward. As discussed in Chapter 1, two groups of theories are proposed. The first one argues for the formation of switchbacks by solar small-scale transient events. The second supports a formation that takes place further away in the solar wind. Both theories are supported by models and observations. For example, [Tenerani et al. \[2020\]](#) used MHD models to study the evolution of large-amplitude Alfvén waves to discuss the origin of switchbacks in the lower corona and showed that they could survive to PSP distances in a calm background solar wind. The key ingredient here is the solar trigger mechanism.

To investigate and provide evidence for the hypothesis of a solar origin, let us now explore what processes lead to magnetic reversals measured in situ. The initial step is to investigate the lower solar atmosphere and an initial physical mechanism required to create a perturbation along an open magnetic field line. This perturbation would then propagate along the field line in the upper atmosphere towards the interplanetary space until it encounters the spacecraft. Some issues can be directly spotted as the perturbation should first survive and then propagate in the solar wind. The processes that create a perturbation in the magnetic field should counteract the magnetic tension of the line so that the perturbation can survive over long enough distances. Some

processes proposed in the literature may not sustain sufficiently long survival of the reversals. One of them is the generation of a reversal of a single field line by interchange reconnection between a small-scale loop and an open field line in the low corona [Fisk and Kasper, 2020].

Among the processes that could trigger switchbacks, there is a growing consensus on the key role played by small-scale energetic events caused by magnetic reconnection in creating conditions for the generation of switchbacks. Indeed, numerous solar studies show that ubiquitous transient events, like, for instance, jets, are able to eject mass, twist, and waves out to the interplanetary space [Raouafi et al., 2016]. Wang et al. [1998] reported that the plasma is ejected with an outflow speed of about 250 km s^{-1} during polar jets identified in EUV bands. Paraschiv et al. [2012] estimated the average ejected mass that could contribute to the slow solar wind flux. The estimated mass is converted to the energy to heat the corona in Paraschiv et al. [2015], with values around 1% of the total energy required. Lee et al. [2014] simulated jets in an emerging flux region and showed evidence of the propagation of Alfvén waves in the corona as the result of an untwisting motion of the structure. These simulations are supported by observations of jet flows reaching the local Alfvén velocity [e.g., Cirtain et al., 2007]. The waves could evolve to result in the magnetic structures observed at PSP. This scenario of the generation of switchbacks, however, is not yet proven. The present analysis aims to thoroughly test the hypothesis of solar precursors of switchbacks, focusing on the theories of small-scale transient events.

Most studies aimed at investigating the solar origin of the switchbacks have focused either on their in situ properties or remote sensing ones of their possible solar sources. The exclusive focus on either switchback measurements or only on solar phenomena constrains the search for conclusive evidence and may potentially bring a clear bias in the interpretation of the data. The direct comparison of recurring eruptive phenomena and switchbacks is very challenging. The lack of conclusive results regarding the origin of switchbacks is largely due to the difficulties of directly connecting transient events measured in situ with transient events that occur in the low corona.

The challenges arise from the inherent complexities of studies that compare the input and output of a complex system involving several physical mechanisms, each adding another layer of uncertainties. The small transient events that were mentioned above, which are observed in EUV images above the limb, quickly mix with the background intensities at large distances in the upper corona as the lower density contrast results in a low intensity in the images. Currently, there is no imaging instrument that would allow us to track these eruptive events to the location of PSP, which is, at best, at 8.8 solar radii from the surface. Additional limitations come from the low cadence and spatial resolution of the instruments that cover a large distance from the Sun. The Large Angle and Spectrometric Coronagraph (LASCO)-C2 coronagraph, for example, provides an image of the corona between 1.5 and 6 solar radii every 20 minutes, with a spatial resolution of $23''$ per pixel. The scales of the eruptive events are below the LASCO-C2 resolving capabilities and, therefore, cannot be detected in the coronagraph images, not to mention the choice of the proper wavelength. The lack of

coronagraph data below $1.5 R_{\odot}$ creates a significant challenge to continuously follow small-scale transients until they reach in situ instruments. There exist ground coronagraphs, e.g. MARK IV, observing close to the Sun, but their spatial resolution is not able to track most of the jets. An EUV instrument, Sun Watcher using Active Pixel System detector and Image Processing (SWAP) on board PProject for OnBoard Autonomy 2 (PROBA-2) is fitted to fill this gap, with a FOV that could overlap LASCO-C2, but we find that the spatial resolution is too low to resolve the scales of eruptive events (see Appendix A).

To bridge the gap between the solar surface and PSP, we then have to rely on models of the magnetic field to determine the spacecraft’s connectivity with the solar surface. This modeling approach is a source of additional uncertainty that impacts the conclusions of the switchback precursors. Some uncertainties can be overcome and tested in the analysis, which is a clear requirement to explore the hypothesis of a switchback source in the lower corona. I will now discuss the solar phenomena currently under investigation as possible precursors of switchbacks.

3.1.2 Possible solar sources

The first evidence for a possible solar origin of switchbacks comes from the occurrence of switchback patches. These appear to be directly related to the solar supergranulation. The latter corresponds to a pattern of cellular flows in the photosphere, with a cell size of 30 Mm, which is called a supergranule, and a typical lifetime of about 1.7 days [Rincon and Rieutord, 2018]. It was first detected through Doppler imaging of the solar surface, which allows us to retrieve the flow velocity along the line of sight [Leighton et al., 1962].

Two studies [Bale et al., 2021; Fargette et al., 2021] found spatial scales in switchback patches whose characteristics are similar to the known supragranular scales. The former authors argue that the magnetic field is shaped in the form of funnels that expand above the supergranules. When PSP crosses structures in situ, the funnels modulate the in situ properties of the switchbacks, forming patches. They also found a correspondence between the in situ measurements of the abundance of helium and the typical ones in the chromosphere. However, these results provide a general perspective, as they connect a large group of switchbacks to a solar network of supergranulation but do not explain how singular events are formed.

Multiple solar candidates have been investigated as possible precursors of individual switchbacks regarding their energy, occurrence rate, and ability to produce perturbations that can escape the corona. We note that sometimes different candidates are generated by the same physical mechanisms, even though they have been given different names because they are observed at different wavelengths or with different instruments, adding confusion to their systematic comparison. Here, I aim to present the variety of phenomena that can be considered, but I will not discuss the used terminology.

Different layers of the solar atmosphere can be considered to be the birthplace of switchbacks. The chromosphere presents different types of transient events, such as

chromospheric swirls [Tziotziou et al., 2023] and spicules [Pontieu et al., 2011]. The swirls are vortex structures that are created by turbulent subsurface convection flows of plasma that interact with the magnetic field. They have a similar scale as granules (about 1 Mm). They also have a coronal counterpart with rapidly rotating structures [Tziotziou et al., 2018]. Spicules are thin and elongated structures observed in the chromosphere. They are investigated as a possible way to bring plasma from the photosphere to the coronal heights, with the observation of a UV and EUV signature that could indicate heating of the plasma to coronal temperatures [Tian et al., 2014]. However, the possibility of a perturbation created at chromospheric heights to propagate to coronal heights and then in the solar wind has not been proven. Most of the energy produced in the chromosphere is known to remain trapped there, and only a small fraction can escape into the corona [Carlsson et al., 2019]. These arguments explain why chromospheric features are excluded from our analysis.

Regions that are more likely to produce events that could escape the solar atmosphere originate in the low corona. It has been investigated by many as it produces various scales of events that could survive into the solar wind, from the largest structures that appear as narrow-Coronal Mass Ejection (CME) in coronagraph images [Wang et al., 1998] to the smallest events that are detectable by current instrumentation [Chitta et al., 2023]. The largest size of transient events that are investigated as possible switchback precursors are solar jets [e.g. Shibata et al., 1992; Raouafi et al., 2016], with an occurrence rate (approximately 1200 per day in all CH regions in EUV coronal images in Huang et al. [2023b]) that could match or at least exceed the occurrence rate of switchbacks (on average 100-600 per hour depending on the threshold of their deflections). Most jets originate from clusters of small-scale loops known as coronal bright point (CBP) [Madjarska, 2019]. Some studies estimated the occurrence rate of CBPs to 570 CBP per day on the disk [Alipour and Safari, 2015]. CBPs are found in all regions of the solar atmosphere, including the QS, CH, and near AR, as seen in Figure 3.1.

Smaller eruptive events are also considered, such as jetlets, which represent smaller-size jets, typically observed at the base of plumes [Raouafi et al., 2023]. Plumes are bright ray-like features embedded in coronal holes, as the base of the plume is often associated with a cluster of small-scale loops. The origin of the plumes is still under debate, but it is suggested to be due to jets, which appear to precede the formation of plumes [Raouafi et al., 2008].

Let us now introduce a classification of jets based on the energy they can propel out of the Sun. However, the classification is still in development because there is no consensus on the existence of these subcategories. Nanojets are produced by nanoflares in closed-loop systems, that are transverse to the magnetic field direction, which have an energy that is about nine orders of magnitude smaller than a flare [Antolin et al., 2021]. They are then not considered further in this analysis. Picojets follow the same reasoning, with their association with the picoflare energy range [Chitta et al., 2023]. Then, another category of low coronal events that could be considered is small-scale brightenings called “campfires” [Panesar et al., 2021]. Campfires are an enhancement of

intensity in the corona detected in the highest-resolution images taken by *Solo*/EUI, which can result from various transient events, including small-scale jets, but also from any other type of events that would create an intensity increase in EUV images.

The size of the eruptive events appears to be inversely proportional to their numbers [Shibata, 1998]. Thus, the smaller eruptive events are more numerous than the relatively large ones. This property, which is shared by most of these events, shows how important it is to specify the size threshold when determining average properties, such as their occurrence rate. Switchbacks are omnipresent in the Alfvénic solar wind, and thus the events that produce the conditions for their generation should be equally numerous or more frequent. They should also be generated throughout the solar cycle in the absence of active regions and large coronal holes. This is a very important condition.

There is then a wide range of energies in jet-like activity that could be investigated, from about 10^{22} erg for the smallest (picojets) [Chitta et al., 2023] to 10^{29} erg for jets in AR [Raouafi et al., 2016]. They appear to be the consequence of reconnection events in the corona, mostly between open and closed magnetic fields, which is defined as interchange reconnection. All jets, whatever their energy, can potentially be the precursors for creating Alfvénic fluctuations that would propagate and create the switchbacks observed in situ. However, further investigations are needed to determine the amount of energy required to create structures that could indeed survive and escape the Sun.

First, it is possible that the numerous smaller and less energetic jets do not escape the corona. The nanojets are not directly associated to switchbacks in the literature, as they occur in closed structures, which would prevent the nanojet to escape the corona. They are mostly investigated for their release of thermal energy in the corona. The campfires will not be investigated in this study, as there is no definite proof they are events that can escape the corona. Second, the picojets are a relatively new category, with observations obtained in the past 2 years [Chitta et al., 2023], which would require further investigation to confirm their properties and energetics. Finally, the undefined occurrence rate of the jetlets and their specific location at the plume footpoints still do not allow one to consider the jetlets as a precursor of switchbacks in this study.

This study will then focus on jets from CBP, with their spatial and temporal omnipresence, and the fact that they can escape in the upper corona and can create perturbations that may evolve into switchbacks. This part of the work was performed in collaboration with Maria S. Madjarska because of her expertise on the CBPs and small-scale eruptions.

3.1.3 Investigated Solar Phenomena: Coronal Bright Points and Jets

3.1.3.1 Coronal bright points

CBPs are clusters of small-scale loops [Madjarska, 2019]. They are observed in EUV [e.g., Zhang et al., 2001] and X-rays [e.g., Vaiana et al., 1973]. They can be interpreted as small-scale ARs. Figure 3.1 shows the full disk in the EUV AIA 193 Å band at solar minimum. Two CBPs are presented in an enlarged field of view, with the loop structure

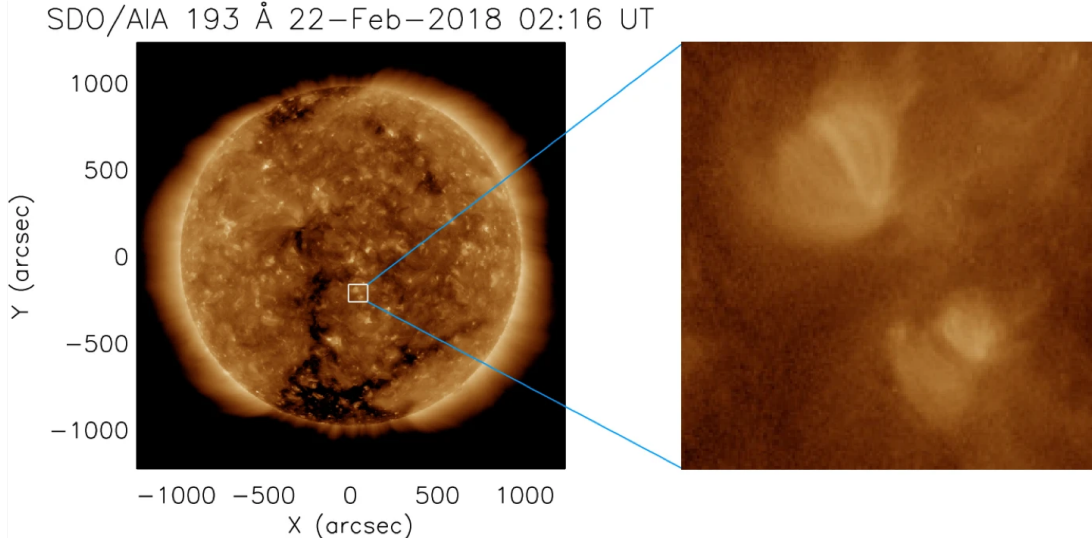


Figure 3.1: Full disk [AIA 193 Å](#) at solar minimum with a zoom in a field-of-view containing two [CBP](#). Reproduced from [Madjarska \[2019\]](#).

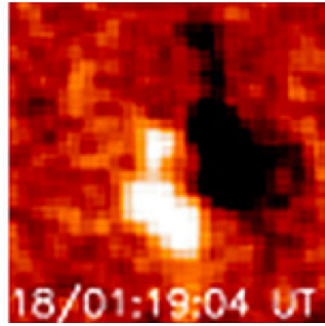


Figure 3.2: Solar and Heliospheric Observatory (SOHO)/MDI magnetic bipole in the photosphere associated with a [CBP](#). Adapted from [Madjarska et al. \[2003\]](#).

that can be observed. To describe their morphology, the loop system is complex, with hotter loops that overlay cooler loops [[Doschek et al., 2010](#)]. The cool loops connect opposite polarities. The bipole system corresponds to magnetic flux concentrations in the network at the boundary between supergranulation cells. An example of a magnetic bipole associated with a [CBP](#) is presented in Figure 3.2.

Let us now introduce the general properties of [CBPs](#). I will first discuss their morphology, then their lifetime and sizes. Historically, [CBPs](#) were first observed in X-rays, then named X-ray bright point (XBP) [e.g., [Vaiana et al., 1973](#)]. They appeared as point-like intensity enhancements with a brighter core surrounded by diffused emission. They were linked to regions with opposite magnetic polarities in the photosphere.

Their lifetime is relatively short, about 20 hours [e.g., [Mou et al., 2018](#)] indicating a relationship to the supergranulation [[Madjarska, 2019](#), and references therein]. Interestingly, this allows one to follow the full lifetime of the structures compared to bipolar

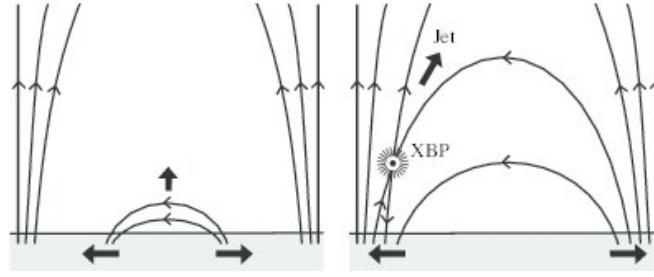


Figure 3.3: Schematic representation of the converging flux model. Reproduced from Poletto and Suess [2004].

AR, with estimated lifetimes ranging from weeks to months for the largest ones [van Driel-Gesztelyi and Green, 2015], or CHs that have been observed over 5 to over 10 solar rotations [Heinemann et al., 2020]. For comparison, a full solar rotation is about 27 days. ARs and CHs exist over multiple solar rotations that prevent their continuous observations over the full lifetime, without gaps.

The size of CBPs (defined as the diameter of the projected area) is typically in the range of 10 to 60'', which corresponds to a range from 5 to 40 Mm, while there is no agreement on the size. Throughout their lifecycle, CBPs evolve in size, often appearing smaller at the initial stage [Mou et al., 2018], and also decreasing in size toward the end of their lifespan.

There are two models about the formation of CBPs that are directly linked to the photospheric magnetic field. One is related to magnetic flux emergence, divergence, and convergence, and the second is the random movement of field lines because of the magnetoconvection. The latter is believed to occur when photospheric footpoints of open or closed field lines converge, leading to magnetic reconnection in the corona and consequent plasma heating (see the next paragraph for details).

The first model was developed in a model by Priest et al. [1994], where opposite polarities of equal strength, first separated, are pushed closer due to photospheric flows. This leads to the formation of a null point, which is pushed to higher coronal heights, as illustrated in Figure 3.3. The plasma can then escape along the newly reconnected field line. The null point then moves down towards the photosphere, where it reconnects. This is the cancellation phase of the model, which corresponds to the full disappearance of the structure.

The second model aims for the random movement of field lines that would bring opposite polarities in the same region and allow for the generation of CBPs. The open or closed magnetic field footpoint motions in the horizontal direction may produce electric currents in different layers of the atmosphere [Santos et al., 2008]. The currents would then dissipate at certain specific locations and produce heat. That would be observed at the same location of CBPs. The most recent benchmarking 3D radiative MHD model that explains the plasma heating trapped in small-scale magnetic loops (i.e., CBPs) is by Nóbrega-Siverio et al. [2023].

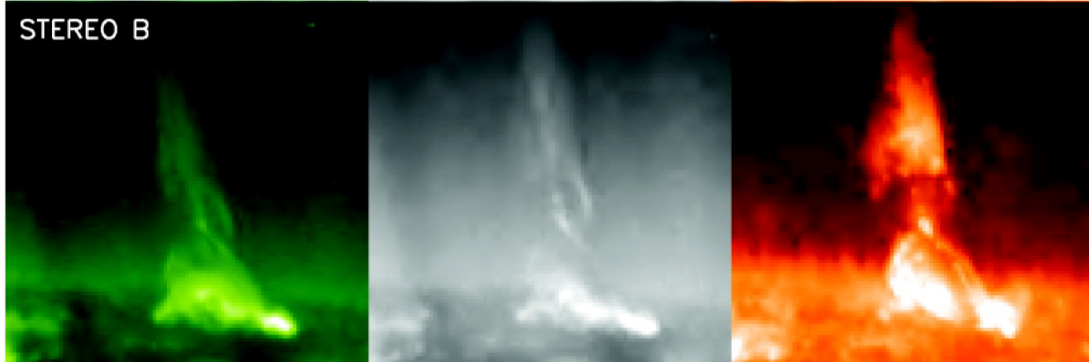


Figure 3.4: Jet observed at the polar CH by the EUVI instrument on board STEREO B in multiple EUV wavelength channels: 195 Å, 171 Å and 304 Å (respectively from left to right). Reproduced from [Patsourakos et al. \[2008\]](#).

3.1.3.2 Jets from CBPs

The main interest in CBPs resides in the eruptive events they produce, the jets. Jets from CBPs are dynamic events resulting from magnetic reconnection. They manifest themselves as collimated plasma flows along open or closed magnetic field lines. Figure 3.4 shows a jet as observed at the limb, in a polar CH, by the EUVI instrument on board STEREO-B in multiple EUV wavelength channels.

Although jets are observed in multiple wavelengths, they do not always have a counterpart in all the wavelengths. As for CBPs, jets were first observed in X-rays and were called X-ray jets. They were observed as brightness increases by several orders of magnitude, which occurred on short time scales of a few minutes [\[Golub et al., 1974\]](#). The first X-ray jets were identified as collimated flows by [Shibata et al. \[1992\]](#). They originate from XBPBs but also from ARs. CBPs also produce jets observed in white-light coronagraph images [\[Paraschiv et al., 2010\]](#).

The jets were analyzed with spectral instrumentation in [Kamio et al. \[2011\]](#) and [Madjarska \[2011\]](#). They observed that, as for the events with emission in EUV, the measurements show a first emission peak at high formation temperatures. Several minutes later, a peak in the cooler emission is observed, which is typical of EUV observations of cooling [e.g., [Viall and Klimchuk, 2012](#)].

A major observation for our investigation is that most CBPs produce at least one eruption during their lifetime [\[Mou et al., 2018\]](#). Eruptions from CBPs occur during the magnetic flux convergence stage rather than during the flux emergence stage. The eruption usually occurs at the end of the lifetime of the CBP, around 17h after the first observation of the CBP [\[Mou et al., 2018\]](#). Repetitive eruptive events during one jet were reported in [Madjarska \[2011\]](#).

Interestingly, the location of the CBP influences the properties of the eruptive events [\[Kamio et al., 2011\]](#). When a CBP is located in a CH, the CBP eruptions are jets. That is possible because of the predominant open magnetic field configuration. In contrast, in the QS, CBP eruptions produce dimmings typically associated with (mini) coronal

mass ejections, where expanding loops remove the overlying corona, which leads to a region of smaller density that appears as a dimming in EUV images. Occasionally, the dimming region contains chromospheric plasma associated with eruptive (mini)-filaments that also appear in absorption.

Jets have speeds often as high as a few hundred kilometers per second. The velocity varies with wavelengths and with instrument techniques used. X-ray jets with velocities from 300 to 1000 km s^{-1} were reported [Strong et al., 1992]. In white-light jets, the velocity is in the range 180 to 380 km s^{-1} [Paraschiv et al., 2010]. In EUV, different measurement techniques based on STEREO observations reported velocities in the range 250 to 400 km s^{-1} [Raouafi et al., 2016]. The numbers provided here report the velocity of the plasma, as faster components, associated with waves, have been detected (about 800 km s^{-1} , with velocities close to the local Alfvén velocity [Cirtain et al., 2007]. These velocities are of interest for determining whether the jets could survive and propagate out of the low corona. This opens up the question of the physical parameters we should consider. Indeed, the Alfvén waves produced at higher velocities may be more likely to escape the corona, whereas the bulk plasma may decelerate and fall back to the surface. We should now discuss the observation of jet propagation.

3.1.3.3 Propagation of the jets

A subpopulation of jets can escape the solar corona, following open magnetic-field lines [e.g. Wang et al., 1998; Nisticò et al., 2009; Paraschiv et al., 2010]. That is promising, as I want to investigate whether these jets can be linked to the switchback structures that are observed in situ. In the absence of proof of the relation between jets and switchbacks, one should discuss the nature of the perturbations that could be the switchback precursors.

Hanaoka et al. [2018] discussed the acceleration profile of the bulk plasma of the jets during their upward movement. Patsourakos et al. [2008] showed the slow initial ascent of the jet followed by an acceleration that allowed the jet to overcome solar gravity. The jet decelerates at higher altitudes to reach the background solar wind speed [Wang et al., 1998]. However, after a few solar radii that can be observed by the existing instrumentation, there are no remote sensing observations of the events that could provide information on the physical processes that take place. Then, it is crucial to find models that could simulate the propagation of jets and waves to distances that are larger than the radial distance of PSP to the Sun. Roberts et al. [2018] showed in simulations of the propagation of jets that the plasma jet assimilates into the ambient plasma, and only the Alfvénic fluctuations survive. Similar simulations are currently investigated in Touresse et al. [2024] and in Wyper et al, in preparation¹, based on the same code as Roberts et al. [2018]. These studies show that magnetic “untwisting” waves can survive until they reach PSP and beyond. It then appears that the magnetic waves produced by jets could potentially lead to deflections of the magnetic field lines

¹The work was presented at the 17th European Solar Physics Meeting ESPM-17. Their work is based on the same code as Touresse et al. [2024].

at larger distances. However, it is still unclear what processes could generate the full reversals. That is, while it is easy to generate deflections of less than 90° , that of larger deflections is still an open question [E. Pariat, private communications].

3.1.4 Description of the procedure

After introducing the reasons why we focus on jets from CBPs, let us now combine in situ measurements of switchbacks with remote sensing observations of jets from CBPs in an effort to investigate a causal connection between them. Switchbacks will be determined with the in situ measurements presented in Section 3.2.1, as introduced in Chapters 1 and 2. The remote sensing observations of jets will be based on EUV images that will be introduced in Section 3.2.2. The procedure will be the following:

1. Determine the periods of interest in the encounters of PSP with the Sun;
2. Determine the connectivity of PSP with the Sun to locate the source region of the wind measured by the spacecraft;
3. Determine the number of jets occurring in the source region determined by the previous steps;
4. Compare the in situ time-series of switchbacks with the time-series of the number of jets.

In doing so, I aim to consider the main sources of uncertainty that we can account for. Clearly, some limitations cannot be solved yet and will require further studies. I focus on cases with clear connectivity that occurred during synchronous solar and solar wind observations so that I can make a co-temporal analysis of remotely detected eruptive events and in situ switchbacks. That highly limits the number of cases I can study with relative trust. I then aim to estimate precisely the propagation time that allows one to overlap the in situ time-series with the time-series of the eruptive events. Any significant correlation between the two may then potentially be seen as a signature of a causal connection.

Although this study is the most detailed approach to date, the results show no clear correlation. Different reasons will be considered. They are mostly related to the scales involved in this study, as well as the transient nature of the phenomena investigated compared to the modeling techniques that have to be applied and the lack of understanding about the propagation behavior of the jets in the solar wind.

3.2 Data

Let us now consider what type of in situ observations will be used, followed by the remote sensing ones.

3.2.1 In situ measurements of switchbacks

The in situ data I use in this analysis were presented in Chapter 2. At this stage of the work, I also use the catalog of switchbacks presented in Section 2.2.5, with an extended version that covers more Encounters from E01 to E17. The extended version of the catalog was not available at the time of the study presented in Chapter 2, but was fully validated for the study presented in this chapter. It allows me to investigate most of the past PSP encounters with a larger set of different solar and plasma conditions. The main goal is to ensure that it would not be the limiting factor in this study, with no limitation in the cases I can investigate. The magnetic field measurements are from the MAG instrument (see Section 2.2.2). I use the same methodology as in Chapter 2 for retrieving switchbacks in the catalog, including the Parker spiral reference, the normalized deflection parameter z , the quality factor, and the duration and deflection thresholds. The proton velocity is retrieved from SPC or SPAN-I depending on the availability and reliability of the measurements for each encounter (see Section 2.2.4).

3.2.2 Images of the solar corona

The CBPs and the jets they produce are best observed in EUV images. Multiple space missions observe the Sun at these wavelengths. This work mainly uses data from the Solar Dynamics Observatory (SDO) [Pesnell et al., 2012], which provides continuous observations since 2010. On board SDO, the EUV instrument is called Atmospheric Imaging Assembly (AIA) [Lemen et al., 2012]. The instrument captures the full disk in 6 EUV wavelengths. The cadence of the instrument is 12 s, for a FOV of $41' \times 41'$. The temporal resolution is high enough to resolve the timescale of the events that I study. The image size is 4096×4096 pixels. The six coronal bands (94 Å, 131 Å, 171 Å, 193 Å, 211 Å and 335 Å) cover a wide range of coronal temperatures. Each band is associated with the emission of multiple ions, whose respective temperature response is presented in Figure 3.5.

I focus mainly on the 193 Å band, which is associated with the best-quality observations of CBPs and is extensively referenced in the literature [e.g., Alipour and Safari, 2015; Mou et al., 2018]. It also allows for a good detection of the boundaries of CH that are dominated by an open field, allowing jets to escape.

All images are downloaded from the Joint Science Operations Center (JSOC)². I use level 1 files, which are pre-processed files that undergo some corrections. However, they have to be processed to be used for science. The common calibration procedure is called `aia_prep.pro` and consists of four steps. First, a pointing correction is applied. It queries the JSOC for the most recent pointing and updates the header. This may include new corrections for the pointing, which have been implemented since the time I downloaded the data. Second, the “registration” is applied. It corresponds to a scaling of the image so that each pixel corresponds to $0.6''$, and it also rotates the image to align the y-axis with the North. Third, comes the degradation correction. The instrument

²<http://jsoc.stanford.edu>

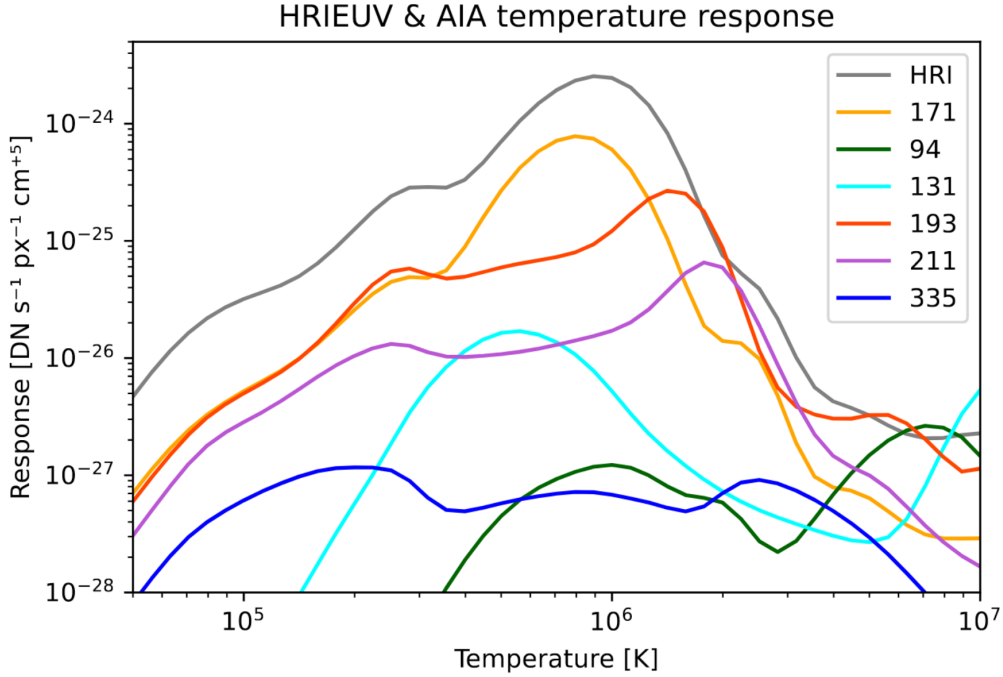


Figure 3.5: Temperature response of the EUV channels in the corona of the AIA instrument. Reproduced from [Dolliou et al. \[2023\]](#).

is subject to degradation over time, which can be estimated and corrected by dividing the intensity by a correction factor. Last is the exposure normalization. The exposure time may vary between two images, which has to be corrected. The final product is a level 1.5 image that will be included in this analysis.

3.3 Connectivity

The major challenge is to connect structures observed in situ by PSP with their solar sources, without the possibility to track their evolution in between. To test our hypothesis, we applied one of the most common methods, based on a process called solar wind back-mapping [e.g., [Badman et al., 2020](#); [Koukras et al., 2022](#)]. The connectivity investigation is based on a two-step standard methodology, illustrated in Figure 3.6. The first step is ballistic mapping following a Parker spiral, which depends on the solar wind velocity until a source surface. The second step is magnetic mapping, based on extrapolation of the photospheric field. The complete methodology is described in the following sections. The connectivity method should determine which open field line is connected to the spacecraft. However, the aim of this work is to investigate a relationship with the transient change of open-field footpoint location in the form of interchange reconnection. Thus, the current methodology will not allow us to precisely determine the connection of the spacecraft with the supposed source near a CBP. Then,

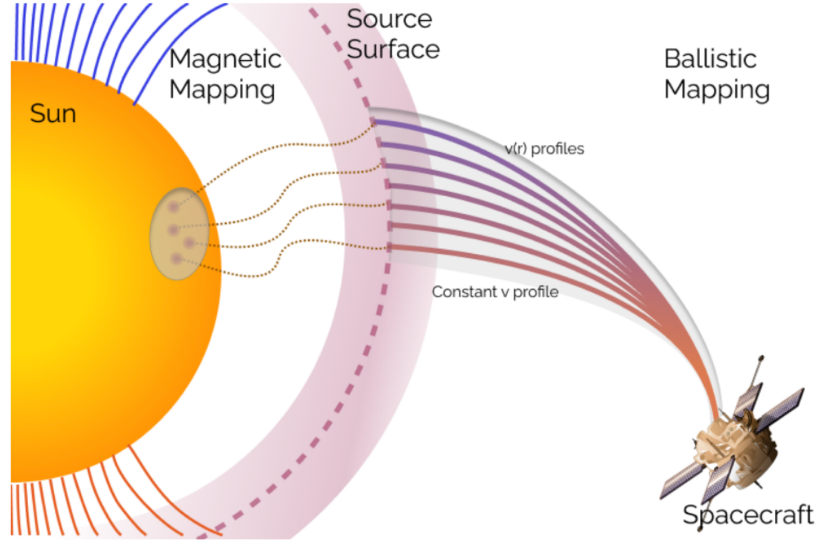


Figure 3.6: Schematic of the connectivity process from a spacecraft to the solar source surface. The first step is ballistic mapping following a Parker spiral, with a parameter of the solar wind velocity. The second step is magnetic mapping, based on extrapolation of the photospheric field. Reproduced from Koukras et al. [2022].

it will only provide the estimated location of the footpoint in an open-field region. The estimated field line connected to PSP would be more likely to undergo interchange reconnection with the closed loops of the nearby CBPs.

The connectivity analysis will be performed on intervals in PSP time-series for which I can retrieve co-temporal images of the solar surface. First, I will start with their identification.

3.3.1 Identification of the interest intervals for our analysis

The procedure starts with the determination of the periods of interest. I studied 17 encounters of PSP of about 10 days duration over a period starting in 2018 to 2023. One of the clear benefits of PSP for such an analysis is the presence of corotation intervals, which correspond to periods where PSP is corotating with the Sun, that is, when the PSP Carrington longitude remains constant. Taking encounter 10 (E10) as an example, Figure 3.7 shows the corotating part of the encounter in red, with the almost constant Carrington longitude. I focus on these intervals because they show an increased probability of measuring the same source for a longer time. This increases the number of eruptive events that can be included in the statistics. It may also allow us to provide cases for which there is a stronger confidence in the connectivity. If the connectivity analysis points to the same source for a long period, it gives us stronger confidence in its unambiguous connection to the structures seen in situ. More importantly, they allow for co-temporal analysis, which is crucial for comparing the solar transient events with in situ switchbacks. Indeed, with single-point spacecraft

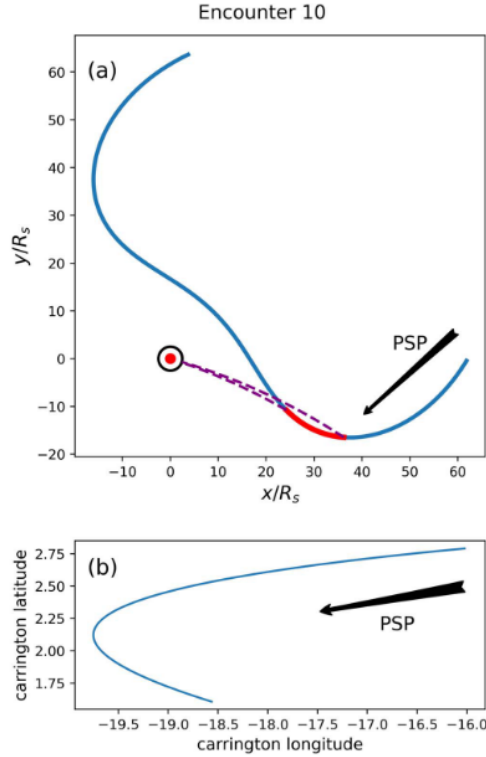


Figure 3.7: Trajectory of PSP (blue curve) in encounter 10 projected on the solar equatorial plane. The reference frame is corotating with the Sun. The red circle represents the Sun. The red part of the trajectory is the inbound corotating interval. (b) The motion of the magnetic footpoint of PSP on the source surface derived by ballistic projection during the corotating interval in red. The horizontal and vertical axes are the Carrington longitude and Carrington latitude, respectively. In both panels, the black arrows indicate the direction of the PSP motion. Reproduced from Shi et al. [2022].

measurements, it is challenging to disentangle spatial and temporal effects that occur when PSP crosses structures from different origins. However, one should note that it is impossible to state that spatial effects can be ignored during corotation events.

For each encounter, I compute the Carrington longitude as a function of time to find the corotation intervals. Then, I have to ensure that solar images are available and that PSP is connected to the visible side of the solar disk as seen from the Earth. The fastest way is to use the Magnetic Connectivity Tool³, developed at IRAP [Rouillard et al., 2020]. The model is similar to the two-step methodology I will use in this study and will be introduced in the following sections. The model, while showing an estimation of the region connected to the spacecraft, is presented as a black box, with fixed parameters. I want to explore the parameters in this study using my own

³<http://connect-tool.irap.omp.eu/>

implementation of connectivity. The tool is used to allow for the direct removal of some corotation intervals when the footpoint provided shows a connection outside the visible disk. The Connectivity Tool will not be used again in this analysis. Finally, I have to check if there are available switchback data for the current list of intervals since I use the catalog of switchbacks, which includes the switchbacks detected in the time-series of PSP [T. Dudok de Wit, private communications].

Table 3.1 presents all the intervals of interest in this study, with the start and end of the corotating interval and the number of the corresponding encounter. At this stage, it shows which cases are excluded, even before the connectivity procedure is carried out, by an “X” in the “On disk” column, as the Magnetic Connectivity Tool gives the source region outside the visible part of the disk. All the cases that respect those conditions are then considered for the next step of the connectivity procedure, starting with the ballistic mapping. The remaining columns will be introduced in the following sections. Here, 19 cases out of 33 are removed. This is clearly a limiting factor.

3.3.2 Solar wind ballistic mapping

3.3.2.1 Model

First, a ballistic backmapping is performed to determine the radial evolution of the solar wind measured by PSP back to a source surface [Nolte and Roelof, 1973]. This requires two steps that are detailed below. The first one is to produce the spacecraft trajectory in the Heliographic Carrington frame, a frame that moves with the Sun. The second step is to project the trajectory down to the source surface using the Parker spiral.

For the first step, I use *astrospace*, a Python package. That allows retrieving PSP Spice kernels, which are objects that contain the PSP trajectory at specified timestamps. Then, I request a series of times for the spacecraft position. It provides the coordinates of the spacecraft in a certain coordinate frame. It is then converted to a Heliographic Carrington frame.

For the second step, the idea is to go from the location of the spacecraft down to the region extrapolated by the magnetic model. Then, from the magnetic model, I will trace the field lines that are connected to the spacecraft and find the source region. This model and extrapolation are detailed in the following section. This second step is achieved with the assumption that the connection is a Parker spiral. Then the latitude is constant, and the only free parameters are the longitude and the radius.

The equations of the Parker spiral are as follows:

$$\begin{aligned}
 B_R(R, \theta, \phi) &= B(R_0, \theta, \phi_0) \left(\frac{R_0}{R} \right)^2 \\
 B_\theta(R, \theta, \phi) &= 0 \\
 B_\phi(R, \theta, \phi) &= -B(R_0, \theta, \phi_0) \frac{\Omega_\odot R_0}{V_{SW}} \frac{R_0}{R} \sin \theta
 \end{aligned} \tag{3.1}$$

Index	Time start	Time end	Encounter	On disk	Connectivity	Jets Counts
1	201811020600	201811040000	E01	✓	X	/
2	201811080000	201811090000	E01	X	/	/
3	201903311200	201904031200	E02	✓	X	/
4	201904061200	201904090000	E02	✓	X	/
5	201908291200	201908300000	E03	X	/	/
6	201909040000	201909050000	E03	X	/	/
7	202001251200	202001261800	E04	✓	X	/
8	202002010000	202002060600	E04	X	/	/
9	202006031200	202006050000	E05	X	/	/
10	202006100000	202006110600	E05	✓	X	/
11	202009231800	202009241800	E06	X	/	/
12	202009291800	202010010600	E06	X	/	/
13	202011040600	202011050600	E07	✓	X	/
14	202011020600	202011060600	E07	X	/	/
15	202104260000	202104270600	E08	X	/	/
16	202105011200	202105021800	E08	✓	X	/
17	202108061200	202108071800	E09	X	/	/
18	202108180000	202108130000	E09	X	/	/
19	202111180000	202111191200	E10	✓	✓	✓
20	202111230000	202111250000	E10	X	/	X
21	202202221800	202202231200	E11	X	/	/
22	202202271800	202202281800	E11	X	/	/
23	202205300000	202205031000	E12	X	/	/
24	202206031800	202206050600	E12	✓	X	/
25	202209300000	202209041200	E13	✓	✓	X
26	202209080000	202209091200	E13	X	/	/
27	202121080000	202120910200	E14	✓	✓	X
28	202212131200	202212150000	E14	X	/	/
29	202303200000	202303210000	E15	X	/	/
30	202303200000	202303210000	E15	✓	✓	✓
31	202306190000	202306200000	E16	X	/	/
32	202306241200	202306250200	E16	✓	X	/
33	202309250600	202309260000	E17	✓	X	/

Table 3.1: Intervals of interest summary. They correspond to all the corotation intervals of PSP from E01 to E17, format in YYYYMMDDHHMM. The highlighted lines correspond to the cases presented and discussed in this Chapter. The green cases are the cases that can fully be studied, while the orange cases show a unique source region but the identification of the escaping jets is complex. The cases highlighted in blue are examples where the connectivity provided by the Potential Field Source Surface (PFSS) is ambiguous.

with $\Omega_{\odot}$ representing the solar angular velocity rate with respect to distant stars so that they are considered at rest compared to the movement studied, and V_{SW} representing the solar wind velocity.

For a fixed solar wind speed, the longitudinal offset for the spiral connecting points at radii r_0 and r_1 is:

$$\Delta\phi = \Omega_{\odot} (r_1 - r_0) / V_{SW} \quad (3.2)$$

Here, the velocity of the solar wind is retrieved from in situ measurements at the spacecraft location. Note that in the case of a corotation with the Sun $\Delta\phi = 0$.

At this stage, we have the connection from the spacecraft to a source surface, which is at a certain height above the solar surface. The magnetic field in the region below this source surface cannot be approximated as a Parker spiral field. Indeed, since the plasma β drops below 1, the plasma motion does not force the magnetic field movement anymore, but the magnetic field drives the plasma motion. The determination of the field should then be based on MHD equations, and one cannot simply use the Parker spiral model.

3.3.2.2 Estimation of the velocity

In the ballistic mapping model, a critical free parameter is the solar wind velocity V_{SW} and its radial profile. That parameter is set to be constant for the definition of the Parker spiral, which is a significant assumption. Indeed, it neglects the acceleration of the solar wind. However, this acceleration is counterbalanced by the corotation of the solar wind so that the ballistic model still gives a reasonably accurate footpoint [Nolte and Roelof, 1973]. Koukras et al. [2022] estimated the use of constant velocity profiles over acceleration profiles to induce a difference of 10 degrees on the identification sources in the Carrington maps.

Figure 3.6 illustrates the implementation of different velocity profiles. They reach different positions on the source surface, which dramatically changes the region connected to the spacecraft. To solve this issue, one could be tempted to implement a model with acceleration instead. However, correct models of the solar wind velocity are difficult to retrieve and are not guaranteed to give better estimations of the propagation behavior of the wind. This is mostly due to the absence of observations in the middle corona, which could constrain the model [West et al., 2023]. Note that the assumption of a constant profile has more impact when the connectivity is performed for spacecraft at 1 au. In my study, PSP is much closer to the Sun, which reduces the impact of different acceleration profiles that could be used to model the propagation of the wind. This is supported by Dakeyo et al. [2024], who found relatively small errors at the location of PSP. I will nevertheless study the influence of different acceleration profiles. It can be approximated with simple correction of the constant velocity to account for different acceleration profiles and, thus, different time delays in the propagation.

I implement the correction with a computation of the ballistic mapping with the velocity measured at PSP as an input and subsequent computations with a correction of

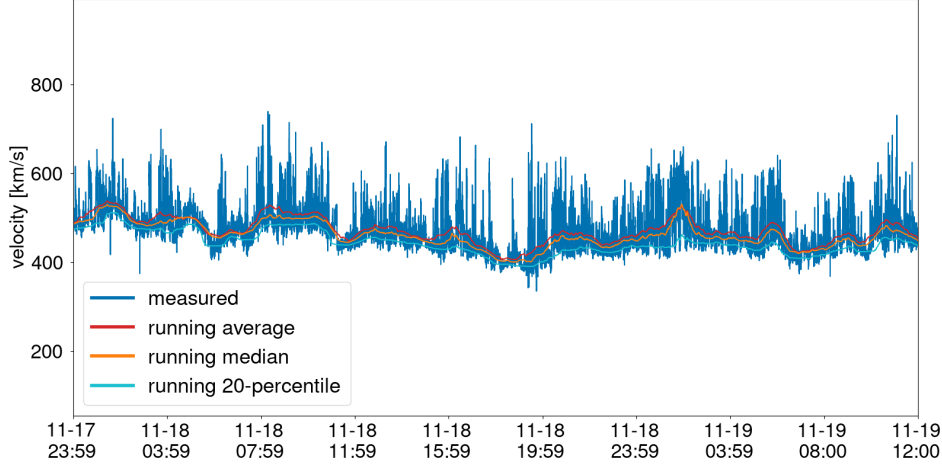


Figure 3.8: Proton velocity measured at PSP and smoothing filtered applied to estimate the velocity used in the backmapping step of the process. The duration of the running windows is 17 minutes.

$\pm 80 \text{ km s}^{-1}$. These values are used in Panasenco et al. [2020]. The negative corrections are implemented to correct the acceleration profiles, which are equivalent to slower winds, while the positive corrections correspond to the propagation of structures at the local Alfvén velocity, faster than the background solar wind. I will discuss the selection of these values related to solar wind velocity models in Section 3.4.4.

Now that the model and the correction are set let us discuss the in situ velocity measurements. The velocity measurements used in this analysis are SPAN-I protons moments. As discussed previously, SPAN-I is dependent on its FOV. However, these are the only measurements available in situ and have been used in other studies [e.g., Badman et al., 2023], as at the time of the corotating intervals, SPC data are not available.

In the SPAN-I time-series presented in Figure 3.8, one can see the variability of the velocity, with velocity spikes associated with switchbacks. The increase is usually of the order of the local Alfvén velocity. As the velocity is highly fluctuating, the proper velocity chosen for the ballistic backmapping is critical. Indeed, I could take the bulk solar wind, estimated with some averaging process. However, I investigate the connectivity between two types of transient events that may not be advected by the solar wind. As a first estimation, I will take the background plasma velocity to compute the backmapping procedure. However, for the steps where I will closely compare switchbacks with the solar eruptive events, I will estimate the influence of such an assumption in Section 3.4.5. That shows another level of complexity in this type of analysis.

For the ballistic backmapping estimation, I consider different smoothing procedures

to determine the local background estimation: a running average, running median, and running 20-percentile. They are presented in Figure 3.8. The time-series are similar, while some techniques appear to be more sensitive to the velocity increases due to switchbacks. I select the running average for the backmapping because I want to conserve the local variability that is not due to the switchbacks. The 20th percentile estimation appears to underestimate the velocity for certain intervals.

3.3.3 Magnetic extrapolation model: the PFSS

3.3.3.1 Description of the model

The type of model that is most widely used to extrapolate photospheric magnetic field measurements is the PFSS [Altschuler and Newkirk, 1969]. This is a relatively simple model that does not require large computer resources. The main assumption is that, in the solar corona, we can neglect the electric currents. This major assumption leads to a simple potential field. The potential field will tend to force the field line to get the simplest topology with the lowest energy, with both ends connected to the surface. A boundary constraint should then be set to model the effect of the solar wind outflow.

Due to the impossibility of accounting for the storage and release of magnetic energy, numerous solar phenomena cannot be resolved with PFSS models [Mackay and Yeates, 2012]. That includes large eruptions such as flares and coronal mass ejections but also smaller eruptive events, such as the jets I am investigating. Thus, the PFSS model should not be used to resolve the small-scale dynamics, only to determine the open field configuration that would be connected to the spacecraft.

The model starts from the ideal MHD momentum balance equation:

$$\rho \left(\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} \right) + \nabla p - \mathbf{J} \times \mathbf{B} - \rho \mathbf{g} = 0. \quad (3.3)$$

Then, we can assume that the corona is static compared to the photospheric timescales. This is valid as the density of the photosphere is larger than the density of the corona, with eight orders of magnitude difference. With a static corona, we have $\partial/\partial t = 0$ and $\mathbf{v} = \mathbf{0}$. Thus, the magnetohydrostatic momentum balance equation is as follows:

$$\nabla p - \mathbf{J} \times \mathbf{B} - \rho \mathbf{g} = 0. \quad (3.4)$$

We consider a corona with a plasma β below 1. Changes in the length scales of coronal structures are shorter or comparable to the typical coronal scale height defined as $H = p/\rho g$. Thus, Equation 3.4 reduces to the force-free equation, which implies that $\mathbf{J}$ and $\mathbf{B}$ are aligned:

$$\mathbf{J} \times \mathbf{B} = \mathbf{0}. \quad (3.5)$$

The general solution to this equation would be as follows:

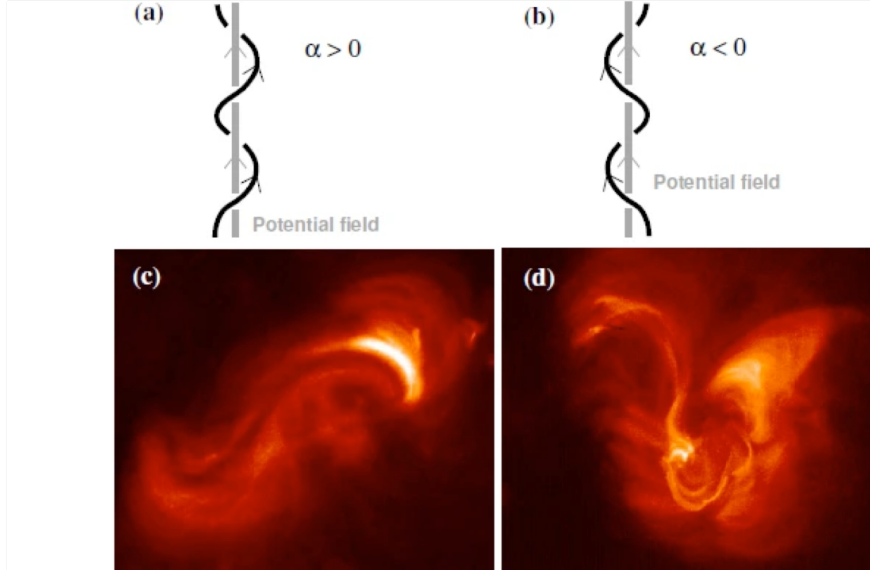


Figure 3.9: Influence of twisted magnetic field, with the parameter α . It shows the potential field configuration $\alpha = 0$, compared to the more complex topology when $\alpha \neq 0$. Panels (c) and (d) show sigmoid structures observed in X-ray by Hinode. Reproduced from [Mackay and Yeates \[2012\]](#).

$$\nabla \times \mathbf{B} = \alpha \mathbf{B}. \quad (3.6)$$

With α , a scalar function that depends on the local geometry of the field lines, which defines the twist in the magnetic field.

This can be coupled with the solenoidal condition for $\mathbf{B}$, which will be performed at a later stage:

$$\nabla \cdot \mathbf{B} = 0. \quad (3.7)$$

Interestingly, if we consider Equation 3.6, the solenoidal condition implies that the α function is constant along the magnetic field line.

The simplest solution for Equation 3.6 is obtained by assuming that there is no current density $\mathbf{J} = 0$. This gives a potential magnetic field, which would correspond to the solution when $\alpha = 0$. We now have the current-free equation

$$\nabla \times \mathbf{B} = \mathbf{0}. \quad (3.8)$$

At this stage, it is now impossible to use the model to simulate complex magnetic structures, such as sigmoids, as presented in Figure 3.9. Sigmoids are S-shaped loops that are observed in ARs and is known to be a precursor of a solar eruption [[Pan et al., 2022](#)]. Any structure that includes a certain level of magnetic twist, similar to sigmoids, will not be determined with a potential field.

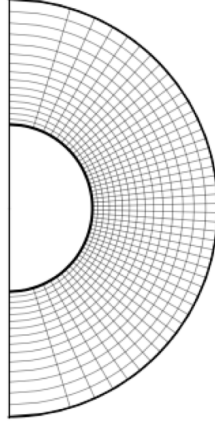


Figure 3.10: Longitudinal slice of the grid on which the PFSS is solved. The lower half-circle is the solar surface, while the larger one defines the source surface. The grid distribution is done in $\cos(lat)$ and $\log(r)$.

The magnetic field can now be expressed as a gradient of a scalar potential ϕ_B , which gives $\mathbf{B} = -\nabla\phi_B$

With the solenoidal equation, we then have

$$\nabla \cdot \mathbf{B} = -\nabla^2\phi_B = 0. \quad (3.9)$$

Thus, the scalar potential obeys the Laplace equation.

The PFSS solves the equations 3.8 and 3.7 in a spherical shell $1 < r < R_{ss}$, i.e. a shell between the photosphere at $r = 1R_s$ and an outer boundary called the spherical source surface, predefined at a certain radius $r = R_{ss}$. The outer boundary condition sets when the magnetic field becomes fully radial so that $B_\phi = B_\theta = 0$ at $r = R_{ss}$. The field is thus perpendicular to the boundary everywhere. This allows us to approximate the outflow of the solar wind with open field lines at this outer boundary. This purpose was to reproduce the fact that the solar wind plasma drags the field lines in the frozen-in property. The lower boundary condition is that the magnetic field is equal to the radial magnetic field measured at the photosphere.

In this work, I use the *pfsspy* [Stansby et al., 2020], which is a Python implementation of the PFSS. The inputs are a synoptic map of the photospheric magnetic field, the radial height of the source surface, and a number of grid cells in the radial direction, as illustrated in Figure 3.10. The grid is not evenly distributed in radial distance and latitude as the spacing increases at the poles and closer to the source surface. This is the consequence of the even distribution in cosine of the latitude and logarithm of the radial distance. In this work, I define $n_R = 60$, the grid points in the radial direction, and $n_{lat} = 180$, $n_{lon} = 360$, the grid points in latitude and longitude, respectively. This is directly related to the highest resolution of the photospheric magnetic field, which will be discussed next. Then, it computes the 3D magnetic field in the shell, and it can

trace the field lines in the extrapolated volume.

3.3.3.2 Photospheric magnetic field

The processes that I investigate occur all in the lower corona. Coronal magnetic fields cannot yet be routinely obtained due to measurement limitations. This is one of the reasons why I have to rely on magnetic extrapolations. The procedure is then based on the input from magnetograms of the photosphere magnetic field, for which direct measurements are possible.

Information on the photospheric magnetic field is usually obtained through spectropolarimetry with the Zeeman effect [Babcock, 1967]. Some of the emission and absorption lines are sensitive to the Zeeman effect in the presence of a strong magnetic field. The lines are then split into different components. The Zeeman effect also introduces a unique polarization signature that can be described by the Stokes parameters. The circular polarization of the components depends on the magnitude and direction of the magnetic field. The field strength is then reconstructed along the line of sight. This requires a certain strength of the magnetic field. However, in the low corona, the field is much weaker than in the photosphere (about 10 G compared to approximately 1000 G in the strongest magnetic field regions in the photosphere [Wiegmann et al., 2014]) and would not produce enough line splitting. Moreover, the emission lines would be broadened as a result of the high temperature in the corona. The last issue with retrieving the magnetic field of the corona through the Zeeman effect is that the corona is optically thin. This means that the field can cancel along the line of sight on the disk and that we cannot determine where we are sampling the field.

Currently, different instruments are measuring the photospheric magnetic field with different cadences and resolution. The spatial resolution may be a critical aspect, as I work on small-scale events, which may not be resolved in the magnetograms. However, the current limitation of the instrumentation does not allow one to resolve smaller scales. This explains one of the reasons why I will identify a region source and not identify a reconnection event on the Sun directly from the connectivity analysis.

The two different instrumental facilities I have investigated for obtaining the photospheric magnetic field are the Helioseismic and Magnetic Imager (HMI) [Scherrer et al., 2012] and the Global Oscillations Network Group (GONG) [Harvey et al., 1996]. The HMI is an instrument on board SDO designed to study oscillations and the magnetic field of the photosphere. It provides different types of data, including maps of the surface velocity and magnetograms of the photospheric magnetic field. Interestingly, the instrument is capable of retrieving line-of-sight magnetic fields, but it also provides vector magnetograms. The full-disk magnetograms have a spatial resolution of 1'' per pixel. The GONG program is a network of ground instruments located around the world. In the following, the use of GONG acronyms will refer to the data products and not the network. They record the Zeeman splitting and circular polarization of one absorption line in the solar photosphere. They also provide photospheric line-of-sight magnetograms that are deduced from the Zeeman splitting. Full-disk magnetograms

can be obtained every minute with spatial resolution of image scale of $2.5''$ per pixel.

There is a third possibility of retrieving a synoptic magnetogram, with a model based on HMI data called the DeRosa / LMSAL model [Schrijver and DeRosa, 2003]. However, the code computes a magnetic model which provides a synoptic map that could be used back into the extrapolation I want to implement. That also fixes a parameter of the source surface height, discussed in the next section, which greatly increases the uncertainties in the process. This is why I do not investigate this synoptic map.

For the study, I need synoptic magnetograms for the estimation of source regions, binned in longitude vs. latitude over 360° and -90° – $+90^\circ$. Indeed, the extrapolation model presented in the previous section produces field lines over the full solar surface. The magnetograms then include the back side of the Sun as seen from the Earth from earlier times and modified through models of flux emergence and dispersion/diffusion.

The reconstruction of the magnetic field on the far side of the Sun to provide synoptic maps is done with two different methods. One consists of fixing the past measurements of the disk until a full rotation is observed. Thus, a major part of the map is based on old measurements. For HMI, for example, that gives a large volume data product which has to be downsampled for the computation of the extrapolation. The downsampling of a magnetogram may cause several potential issues with synoptic maps [Hayashi et al., 2016]. The other solution consists of a mix of measurements and predictions from the models. The model used here is Air Force Data Assimilative Photospheric Flux Transport (ADAPT) [Arge et al., 2010], which then gives two possible data products: ADAPT-HMI and ADAPT-GONG. ADAPT is a flux-transport model, which starts with an ensemble of realizations and evolves them based on known flux transport processes [Worden and Harvey, 2000]. It allows for filling areas where no recent observation is available. Then, filtering techniques are used to adjust the model output with observation uncertainties. A final verification is performed, comparing the output with observations (e.g., field strength and polarity).

As it is necessary to reconstruct the far side of the Sun, we are dependent on large-scale magnetic configurations that can have a significant impact, such as when active regions appear on the back side of the Sun. These may, in turn, change the shape of large magnetic structures such as streamers, which can potentially impact the connectivity to the spacecraft [Perri et al., 2024]. In this work, I will assume that the reconstruction does not impact the connectivity. In practice, as I want the most rigorous method, I use only the visible part of the map to focus only on the most recent and co-temporal observations, as I only select intervals connected to the disk (see Section 3.3.1 and Table 3.1).

As both products reconstruct the back side of the Sun with similar techniques, the main difference between the two products I am investigating is the resolution of the disk part of the synoptic map. Figure 3.11a shows the synoptic map from ADAPT-HMI with high resolution ($1''$ on the disk) and reconstructed data for the rest of the map. For comparison, a map of the same time from ADAPT-GONG is shown in Figure 3.11b. One can clearly see the lower resolution of the disk part (1°) while it still catches the

main polarities.

A second constraint would be about the time resolution: I consider if the cadence of each data product is sufficient to catch the sources with enough precision. One could think about the lifetime of CBPs, but it is more relevant to consider the surrounding magnetic field. Indeed, jets eject along open field lines. Some estimations of the average timescale for flux replacement are proposed, about 1.5 to 3 days for larger regions in the photosphere [Schrijver et al., 1997], while smaller regions would have a shorter lifetime of 8 to 19 hours [Hagenaar et al., 2003].

Ideally, I would choose the data product with the highest temporal and spatial resolution. However, for ADAPT-HMI with the highest spatial resolution, the time resolution is low, with only one map every six hours. A trade-off is required between the timescale and the spatial scale. It appears to be preferable to find that the source region is stable on short time steps as both magnetograms spatial resolution are still too large to capture the small scales of the interchange reconnection events. Thus, I choose ADAPT-GONG data, with a synoptic map reconstructed every two hours.

Koukras et al. [2022] used GONG magnetograms with uncertainty analysis because they add magnetogram noise to study the influence of low resolution of the photospheric field in such connectivity procedures. They find that the magnetogram noise could give an error of ± 2 Carrington degrees in longitude and almost no impact on the latitude. The error is small compared to the other sources of uncertainties that I will discuss. It also emphasizes the impossibility of connecting the in situ measurements directly to one jet since the two Carrington degrees are larger than the size of a jet (see Section 3.1.3).

At this stage, I can perform a connectivity extrapolation every two hours, which is limited by the cadence to retrieve GONG synoptic magnetograms.

3.3.3.3 Source surface height

The major free parameter in the PFSS model is the source surface height. Its selection has the most important impact on the identified source region, compared to other sources of uncertainties [Koukras et al., 2022]. The surface is usually set at $2.5R_{\odot}$ [Hoeksema, 1984], based on white-light images during solar eclipses at solar minimum [Altschuler and Newkirk, 1969]. This value appears to be the most commonly selected one in the literature and is usually not questioned. However, Koukras et al. [2022] finds that the variation in the height of the source surface from $1.5R_{\odot}$ to $3.5R_{\odot}$ can correspond to a variation of about 15 Carrington degrees for the footpoint of the field line connected to the spacecraft. In this analysis, I find cases with even larger variations, from a source region near the equator to a source in the polar CHs.

When the height of the source surface is investigated in the analysis of the PSP measurements in the literature, it usually corresponds to the selection of a unique height for the entire encounter. The height could be determined as the best match of polarity at the source surface and in situ [Badman et al., 2020]. Figure 3.12 shows the source surface of the PFSS and in situ polarity for the first encounter of PSP. The purpose of this paper is to demonstrate the impact of a lower source surface height

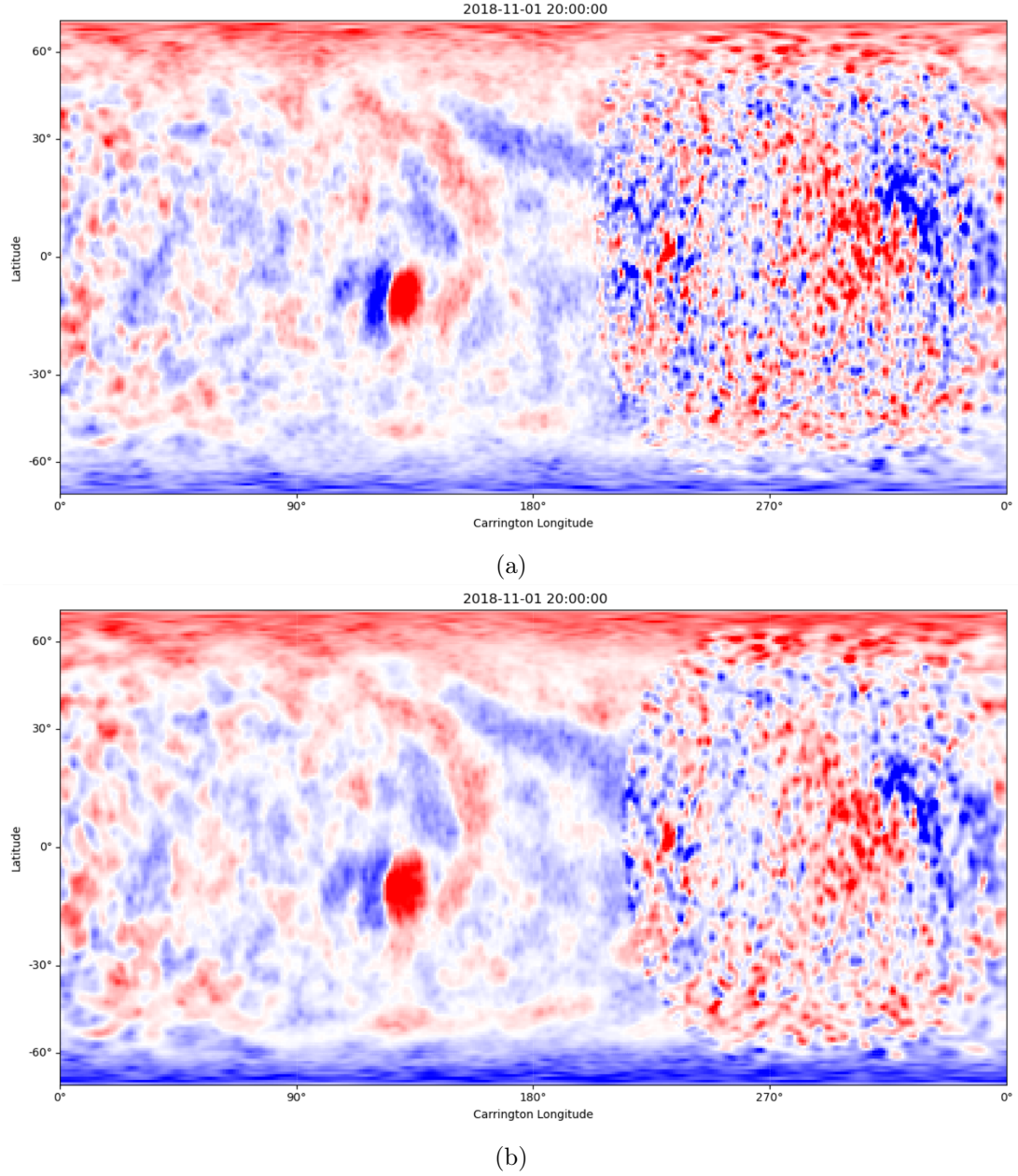


Figure 3.11: Synoptic magnetograms taken in November 01, 2018 and filled with a model to reconstruct the part outside the visible disk. The blue color is negative polarity, and the red is positive polarity. (a) Magnetogram from the combination of HMI observations and ADAPT model. (b) Magnetogram from the combination of GONG observations and ADAPT model.

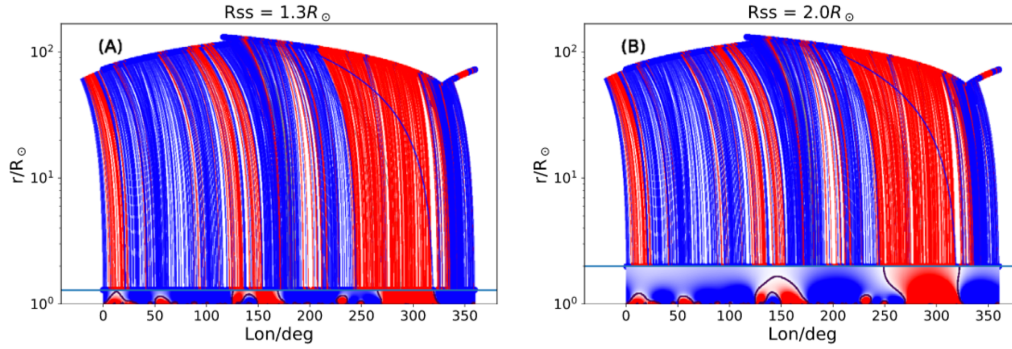


Figure 3.12: Estimation of the source surface height for the first encounter of PSP. The magnetic polarity at the spacecraft is retrieved and plotted on the field lines back to the source surface. Below is shown the polarity at the source surface, retrieved from the PFSS. The two panels show the influence of a different source surface height on the polarity at the source surface that should match the polarity in the in situ measurements at the spacecraft. Reproduced from [Badman et al. \[2020\]](#).

on the local polarity. One can observe that none of the source surfaces gives a perfect match between the two parameters. Some large structures are best captured when the source surface is higher, while smaller, complex structures are captured only at lower heights.

Here I am mostly interested in the CH and open field region determination. [Badman et al. \[2020\]](#) find that this is best estimated for source surface height between 1.3 to $1.5 R_{\odot}$ above the solar surface, by comparing PSP in situ data measured during E01 with AIA synoptic map in the band $193 \text{ \AA}$. However, the comparison is performed on global synoptic maps. As discussed previously, these maps include non-synchronous data, similar to the synoptic magnetograms for the extrapolation. In such conditions, a comparison should only be performed on the synchronous part of the maps when the objective is to find the origin of transient events.

A local estimation can be performed as well, based on a source surface height selection for each polarity change. That results in a non-spherical source surface [[Panasenco et al., 2020](#)]. That allows us to fit each change of polarity with a more precise estimation of the source region. The result of this local estimation provides a non-spherical source surface, which depends on the source region topology.

However, polarity crossing alone is insufficient in the specific conditions of this investigation. I consider transient small-scale eruptive events. They have short temporal and spatial scales and are also not related to global polarity inversions. Thus, I explore the surface heights between $1.5 R_{\odot}$ and $3.5 R_{\odot}$, which are the most common values in the literature.

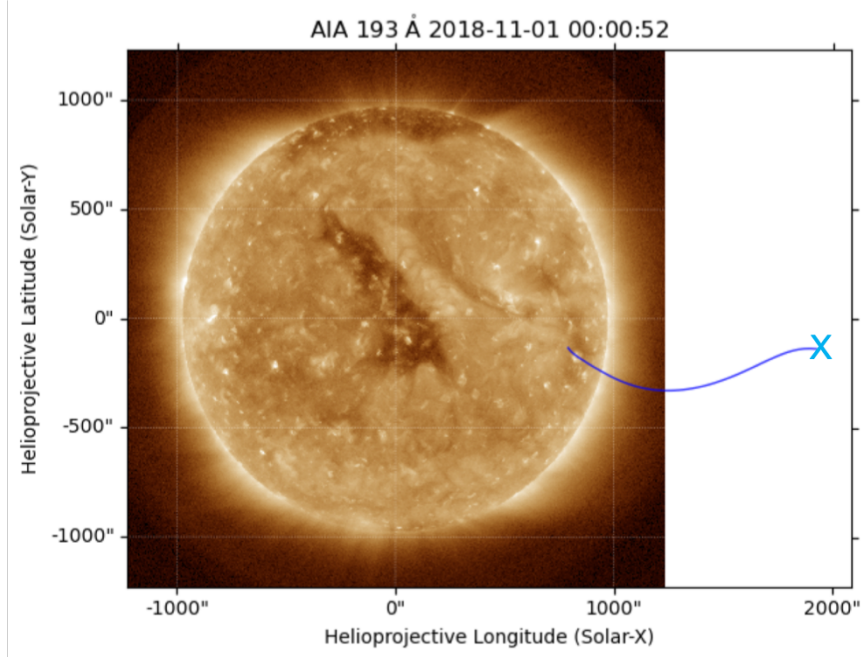


Figure 3.13: Connectivity of PSP during E01. It shows an image taken by AIA at 193 Å at the same time as the computed extrapolation model with overplotted blue-colored magnetic field lines extracted from the PFSS model, computed at a source surface height of $2.5R_{\odot}$. The colored cross marker is the projection of PSP on the source surface.

3.3.4 Case study to investigate the different steps

I will now present the full connectivity procedure applied to a time when PSP was in corotation with the Sun during E01, which corresponds to Case 1 in Table 3.1. The chosen time is November 1, 2018, at 00:00:52.

First, I compute the ballistic mapping and the PFSS at a certain time with a source surface height at $2.5R_{\odot}$, presented in Figure 3.13. The spacecraft appears to be connected to a transient CH, which is near the western limb.

Now, I want to implement the correction of the velocity (see Section 3.3.2.2. Indeed, I first assumed the velocity to be constant as measured by PSP, around 300 km s^{-1} . Now, I again compute the ballistic mapping for different velocities, with a range of $\pm 80 \text{ km s}^{-1}$. These are combined with the computation of the PFSS. Figure 3.14 presents a submap of the solar disk centered on the region approximated by the first PFSS. The input solar wind velocity varies between the different field lines. However, it does not appear to influence the connectivity, as the footpoints of the field lines connected to PSP are still in the same region of the CH. This is what usually occurs in the connectivity cases that I explored. The velocity variation may give variations in longitude and latitude while keeping the connection to the same source region. However, in some cases, the velocity computed with the same source surface height can give a

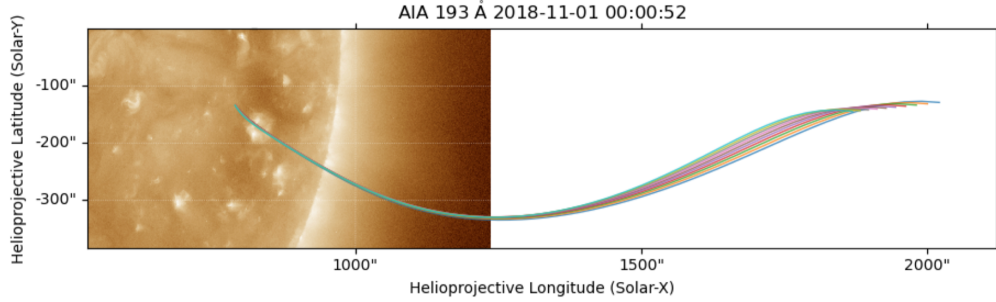


Figure 3.14: Connectivity of PSP during E01 with the implementation of the velocity correction. Similarly to Figure 3.13, an excerpt of an image taken by AIA at 193 Å is shown. The overplotted magnetic field lines extracted from the PFSS model, computed at a source surface height of $2.5R_{\odot}$, are shown with different colors accounting for the different velocities.

connection to different source regions. In such conditions, the event is discarded from the original study and would require future investigation of the source region.

Now, I should consider the influence of the source surface height, combined with the solar wind velocity of the ballistic backmapping. As discussed previously, the source surface is usually set for a long period of time, with a check of polarity inversions. Here, I compute the PFSS extrapolation to different source surface heights. Figure 3.15 shows the implementation of the PFSS for different source surface heights. The implementation of the ballistic mapping with different velocities is then added. The first striking result is that the height dramatically impacts the source region connected to the spacecraft. The errors are larger than the 15 Carrington degrees discussed in Koukras et al. [2022] even though the methods are similar. That may indicate that the cases I consider present a different magnetic configuration. Interestingly, if one considers the polarity of each field line, they are all the same polarity as the in situ measurements at PSP. That would contradict the procedure used in the literature to validate the source surface height. The highest source surface height gives a source region in the southern CH. The slightly lower source surface, at $3R_{\odot}$, connects at a higher latitude at the boundary of the CH. It is difficult to state whether the footpoint is at the limb or in a region close to the limb. The other three source surface heights computed give a source region almost at the equator. Because of the proximity to the limb, the transient equatorial CH is not clearly visible, but can be observed on the disk for several days before.

A second example is a case (Case 10 of Table 3.1) for which the source region appears to be on disk using the Magnetic Connectivity Tool. The connectivity procedure I implement gives different source regions depending on the source surface height. The outbound corotating interval of E05 occurred from June 10, 2020, to June 11, 2020, at 06:00. The corresponding solar interval spans from June 8, 2020, at 18:00, to June 9, 2020, at 22:00.

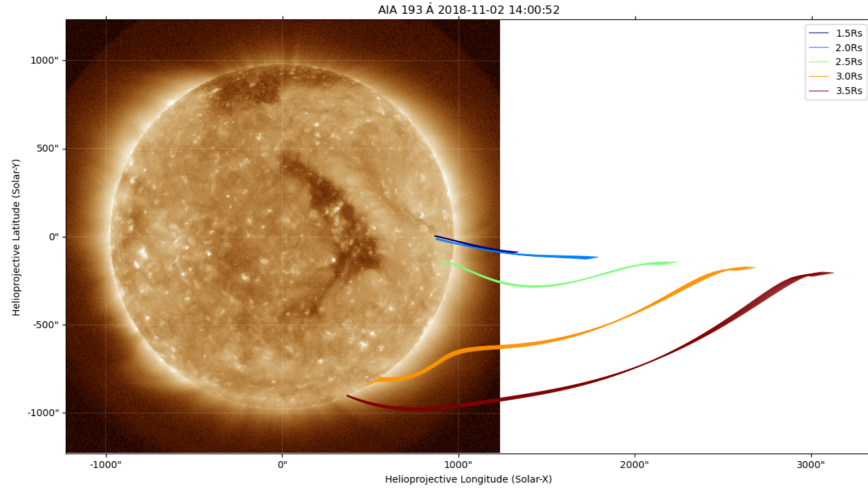


Figure 3.15: Connectivity of PSP during E01 with the implementation of the velocity correction and multiple source surface heights. Similarly to Figure 3.13, it shows a context AIA 193 Å image taken at the same time as the computed extrapolation model with overplotted colored magnetic field lines extracted from the PFSS model, computed at different source surface heights. The multiple field lines of the same color correspond to different velocities.

Figure 3.16 shows one possible connectivity output of E05 corotation, which highly depends on the selection of the source surface height. Not all the footpoints are located in the same CH. Lower heights of the source surface give a footpoint located in a small CH, a higher source surface will give a footpoint in the QS, while an even higher source surface shows connectivity to the northern polar CH.

At this stage of the analysis, there is no reason to choose one source region over the other. However, considering all the uncertainties in the connectivity process, it is very challenging to investigate such cases with the connectivity strategy I apply, using PFSS. I will discuss some perspectives on how to solve the connectivity when it gives multiple source regions in Section 3.6. The periods of interest with similar characteristics, that is, in first approximation, the Magnetic Connectivity tool shows that PSP appear to connect with the Sun on the part visible from the Earth, but then our computed connectivity is ambiguous, are now excluded from the future steps of the analysis. This shows the difficulties in implementing the strategy required to correlate eruptive events with jets. At this stage, only 4 periods of interest remain out of the 33 first considered.

3.3.5 Warnings for future studies

The first step, the connectivity between the spacecraft and the solar source, is crucial and highly depends on the input data. What I observed in the different studies is that it is usually presented on Carrington maps. That implies that the source region

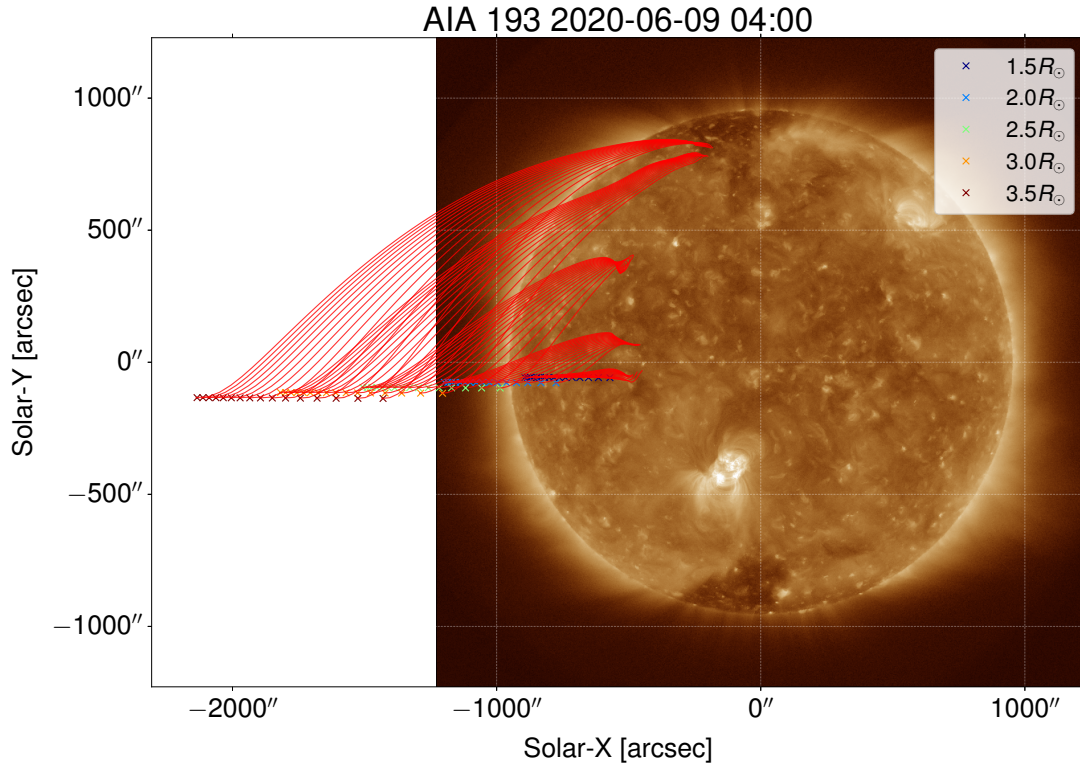


Figure 3.16: The E05 connectivity is shown with a context [AIA 193 Å](#) image taken at the same time as the computed extrapolation model with overplotted red-colored magnetic field lines (positive) extracted from the [PFSS](#) model, computed at different source surface heights. The colored cross markers are the projection of PSP on the different source surfaces. The multiple field lines correspond to different velocities. It shows the inherent limitations of the connectivity, which gives a connection to different source regions depending on the source surface.

stays the same during the time when there are no synchronous data. [Bale et al. \[2019\]](#) focused on the first encounter of PSP. For most of the encounter, the connected source appears to be on the far side of the Sun. That is particularly the case for the corotation interval. From Carrington maps and extrapolation models, the spacecraft is supposed to be connected to an equatorial [CH](#). At the time of the Carrington maps, the [CH](#) is behind the limb if one considers the disk from the Sun-Earth line. In such conditions, the connectivity is based on earlier observations that could induce errors in the connectivity. Some improvement is proposed for similar cases. One can study the source region for more than one Carrington rotation. If the source region is stable, with the same size and level of activity, it can allow reducing the risk of errors [[de Pablos et al., 2022](#)]. However, since connectivity is only the first step, having connectivity to the far side of the Sun prevents the retrieval of remote sensing information, such as the number of jets. One solution here would be to use spacecraft with a side view of the Sun, such as STEREO. However, the time and spatial resolution of its [EUV](#) instrument is lower than [AIA](#). With an image every five minutes, this may prove insufficient if we consider the minimum duration of an eruptive event, as it would increase the risk of missing eruptive events.

3.4 Jets and switchbacks selection and study

The connectivity procedure on the intervals of interest provides a certain number of cases with an unambiguous source region. Now, I will investigate these source regions, using the [EUV](#) images of [AIA](#) presented in Section 3.2.2. First, I present the data processing required to detect small-scale transient events (Section 3.4.1). This initial step is limited not only by the instrumentation resolution but also by the complexity of the field configuration in the source region (Section 3.4.2). Then, I will present an automatic technique used to ease the detection of jets (Section 3.4.3). To allow for comparison with the jets, the switchbacks time-series measured during the interval of interest will be retrieved from the switchbacks catalog I am using. Then, the final step to compare both time-series is to determine the propagation time taken by the solar wind to travel to the spacecraft (Sections 3.4.4 and 3.4.5). That will allow shifting the switchbacks time-series over the jet time-series.

3.4.1 Preparation of the AIA datasets

The first step is to construct a data cube of images that will allow us to study the temporal evolution of the source region. Then, I will identify the jets in the videos computed with the data cube.

Starting from level 1.5 images, I create a data cube of 2 hours duration of [EUV](#) images. To reduce the processing time, I cut the full disk images to select a field of view that includes only the source region. First, I select a submap centered on the region of interest identified by the [PFSS](#). Then, I correct the differential rotation with a derotation code. That part is complex but necessary since I will compare images

from the same region for a relatively long time interval.

The derotation code I used comes from the Rectify package⁴, which can perform image transformations with specific specifications. Here, I am interested in a spherical transform to account for the input image in the helioprojective frame that will be converted to a longitude/latitude map and the differential rotation. Then, it interpolates the data to re-sample images on a regular grid. The reference image is set to be the last image in the selected interval, as the code can only go forward in time.

The differential rotation equation can be written as

$$\Omega = A + B \sin^2(\varphi) + C \sin^4(\varphi) \quad (3.10)$$

with A, B, and C three constants, and φ the latitude computed from the equator. In the Rectify package, the constants are set to $A = 14.5$, $B = -2.14$, and $C = 0.66$, computed from EIT/SOHO images [Hortin, 2003]. This is relevant for AIA 193 Å as EIT has a similar passband.

The next step is to temporally bin three consecutive images to improve the signal-to-noise ratio. Thus, the cadence of the cube is now 36 s between each frame. From this cube, I can produce videos that can be visually processed to detect eruptive events.

3.4.2 Events identification issues

Even when the connectivity appears to be unambiguous, the event detection can then be delicate. For Case 25 in Table 3.1, the connectivity was unambiguously determined by the PFSS. It corresponds to a corotation interval of E13, presented in Figure 3.17. However, the jet identification was difficult due to a line of sight effect due to the position of the estimated source on the disk. In fact, the connectivity appears to be in an open flux region close to a large AR. Moreover, the activity level is low, and it is not easy to disentangle CBP jets from brightenings that could be caused by reconnection in the AR large loops. Overlying loops can potentially hide the CBP, which hinders identification.

A second interval of interest, during E14, and presented in Figure 3.18, showed connectivity to the boundary of an AR, which corresponds to Case 27 in Table 3.1. Figure 3.19 shows three jets identified in this region. They appear to follow closed field lines that are not completely visible in the EUV image. These jets cannot escape the Sun.

3.4.3 Automatic brightening identification to ease the detection of CBP jets

To facilitate the detection of small-scale events and those without sufficient background contrast, a transient brightening identification procedure was used, which involved the calculation of a local background threshold [Subramanian et al., 2010]. In the context of the collaborative project with Maria S. Madjarska, she provided expertise on the

⁴<https://github.com/frederic-auchere/rectify/tree/main>

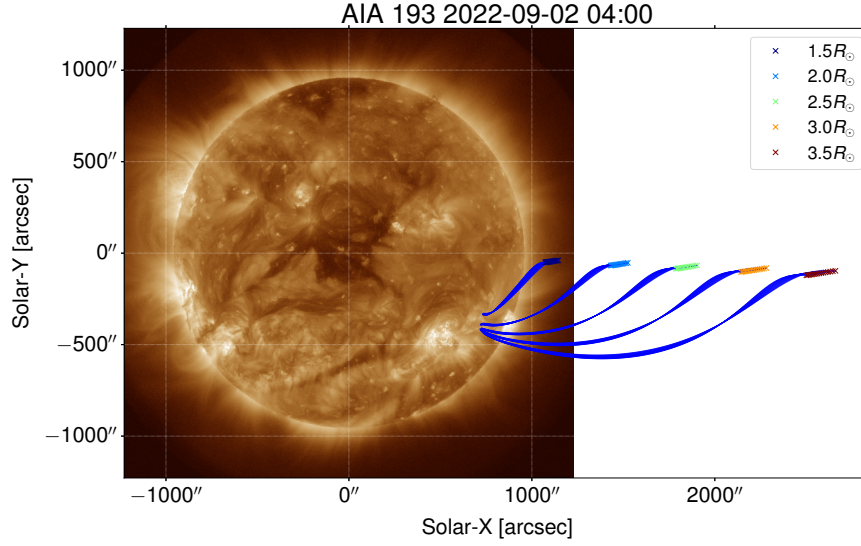


Figure 3.17: The E13 connectivity is shown with a context AIA 193 Å image taken at the same time as the computed extrapolation model with overplotted blue-colored magnetic field lines (negative polarity) extracted from the PFSS model, computed at different source surface heights. The colored cross markers are the projection of PSP on the different source surfaces. The multiple field lines correspond to different velocities. PSP is connected at the beginning of the corotating interval to a near-limb region between two active regions.

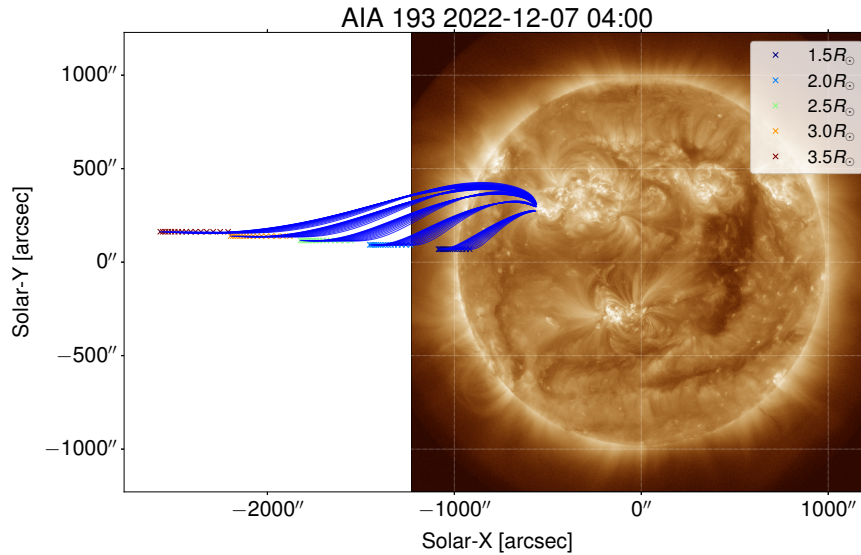


Figure 3.18: Same as Figure 3.17 but for E14. PSP is connected at the beginning of the corotating interval to the boundary of an active region.

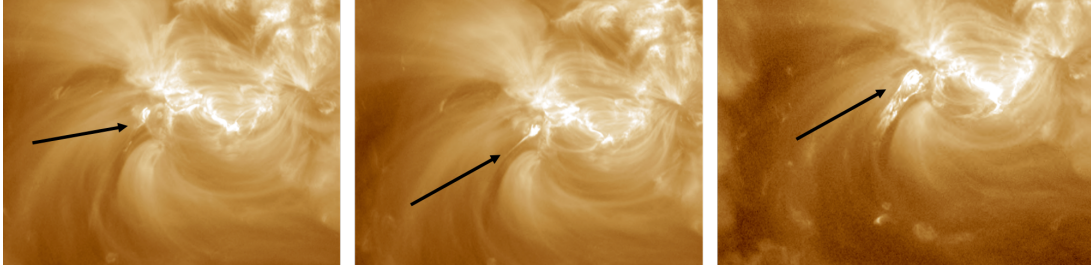


Figure 3.19: Jets identified in the source region given by the PFSS for the E14 corotating interval. The images are taken from [Helioviewer](#).

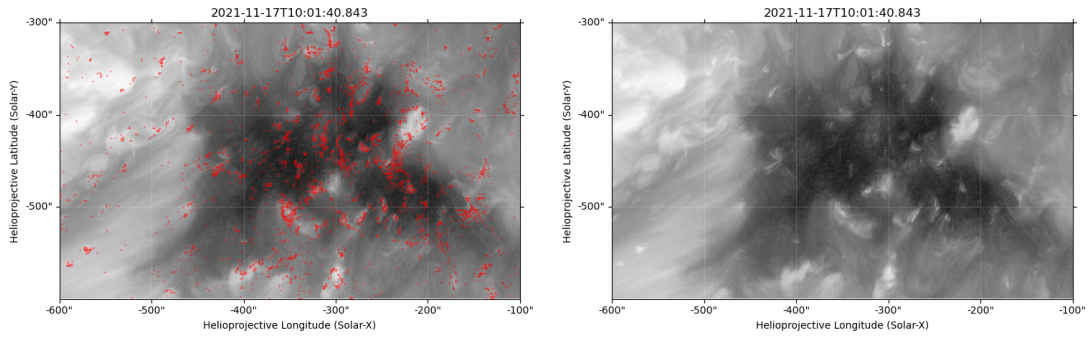


Figure 3.20: Example of a source region processed with the automatic detection algorithm [Subramanian et al., 2010]. The left panel presents all the pixels (red crosses) identified at the specific time of the image, overlapped on the AIA 193 Å image. The right panel is the background AIA 193 Å image for comparison.

brightening identification code. The code works in the time dimension of the cube and not in the spatial dimension; it processes the cube pixel per pixel. Each image is binned to 4×4 pixels², which allows us to reduce the number of points and even further increase the signal-to-noise ratio. Then, a lightcurve is produced for each pixel. A background estimation is performed for each light curve, which allows us to work differently on pixels in the QS from AR, thus keeping the detection effective in all areas of the Sun. A time threshold is applied, removing detections if they last more than 15 minutes. That allows us to remove the detection of the small loops and maintain the transient escaping events. An intensity threshold is also applied to define when the event starts to be detected.

Figure 3.20 presents an example of a source region processed with the automatic detection algorithm and corresponds to Case 19 of Table 3.1. It is visually easier to identify the possible jet location in the FOV. The focus is then on groups of pixels that could have an elongated shape if the jet propagates in a direction perpendicular to the line of sight. If the jet is directed along the line of sight, we could expect to see an area expansion rather than an elongated shape.

The present algorithm is not expected to improve the detection of the two previously

described cases (Cases 25 and 27), as the issues are with the physical processes involved, i.e., the complex topology of the field and the ability to escape the corona in these specific regions, and not with the limitation of the user's visual identification. At this stage, there are only two intervals of interest left, for which the connectivity and the jet identification are unambiguous, namely Cases 19 and 30. I performed an hourly estimation of the number of events per source region for each of them. This will be presented in Section 3.5. Then, I estimated the hourly count of the switchbacks to match the count of jets. The selection of the switchbacks for this analysis is performed with the catalog presented in Chapter 2.

3.4.4 Acceleration models investigated for the shift

I now have an estimation of the number of jets escaping from the source region and the equivalent estimation of the number of switchbacks measured at PSP during the corotating interval. For the comparison of the two time-series, we can now estimate the propagation time of the solar wind that will allow shifting the occurrence time of switchbacks back to their emission time in the lower corona. Here, we have to rely on models to estimate the velocity profile of the solar wind. However, there is currently no consensus on the correct model to use, and I will test different models. There is no hypothesis on the physical mechanisms in the tested models that should be developed in future studies.

As a first step, let's use a constant-velocity profile to estimate the propagation time. For comparison, for the connectivity estimation, the propagation time does not include the acceleration profiles of the solar wind. Different velocities are computed to account for an estimation of different acceleration profiles. However, more precise timings are necessary for the comparison of in situ switchback time-series with remote eruption time-series. For that concern, I discuss possible acceleration profiles that can be considered. The main discussion revolves around the physical processes that should be involved.

There is a wide range of models that describe solar wind propagation and velocity profiles. The original isothermal model from Parker [1958] is the simplest. Similarly to the methodology presented in Koukras et al. [2022], I will use the more complex approximation of the solar wind velocity with different profiles at small and large distances from the Sun. The two profiles are based on the sonic point to distinguish the small and large approximations.

Another physical parameter that should be investigated is the local Alfvén velocity. Indeed, in the case of switchbacks, we have propagating structures in the solar wind associated with a velocity enhancement that is of the order of the local Alfvén velocity. Thus, I first present the solar wind velocity model and then introduce the local Alfvén velocity profile.

Assuming an isothermal corona, the solar wind equation can be derived with a specific sonic point. The original transcendental equation for the isothermal wind profile $u(r)$ at temperature T_0 :

$$\left(\frac{u^2}{a_0^2}\right) - \ln\left(\frac{u^2}{a_0^2}\right) = 4 \ln\left(\frac{r}{r_s}\right) + 4\frac{r}{r_s} - 3, \quad (3.11)$$

with the constant sound speed and sonic point

$$a_0 = \left(\frac{2kT_0}{m_p}\right)^{1/2}, \quad (3.12)$$

$$r_s = \frac{GM}{2a_0^2}. \quad (3.13)$$

As in Koukras et al. [2022], I used a hybrid profile that combined the large and small distance approximation:

$$v_{large} \approx 2a_0 [\ln(r/r_s)]^{1/2}, \quad (3.14)$$

$$v_{small} \approx a_0 e^{3/2} e^{-2r_s/r}. \quad (3.15)$$

Here, the sonic point r_s becomes the free parameter of the hybrid profile, where we locally switch between the small and large distance equation. This differs from the original isothermal wind profile, with a local jump in the derivative. We can constrain the profile using the value a_0 , which depends on the in situ measurement of the velocity of the proton ($v_{S/C}$) and the radial position where it was measured ($r_{S/C}$). We then obtain the following.

$$a_{0_{large}} = \frac{v_{S/C}}{2[\ln(r/r_s)]^{1/2}}, \quad (3.16)$$

$$v_{large}(r) = 2a_{0_{large}} [\ln(r/r_s)]^{1/2}. \quad (3.17)$$

This gives an easy-to-use model for estimating the propagation time. I also computed an isothermal profile combined with a polytropic model at larger distances (at $11.5 R_\odot$) from Sam Badman's open access codes⁵ implementation of the iso-poly model of Dakeyo et al. [2022] that fit the in situ measurements of the solar wind velocity to retrieve the polytropic index. The two modeled velocity profiles are presented in Figure 3.21 (blue for iso-poly model and green for the hybrid profile from Koukras et al. [2022]). There is a clear difference in the profiles, which will result in a large difference in terms of propagation time. Here, for example, for an in situ velocity $v_{S/C} = 489 \text{ km s}^{-1}$ at $40 R_\odot$, the propagation time is 26h20m for the isothermal profile and 19h20m for the hybrid profile.

As discussed previously, an estimation of the Alfvén velocity profile that would account for the Alfvénic nature of the switchbacks should also be considered. For the Alfvén profile, I start from the approximation of the magnetic field magnitude:

⁵ParkerSolarWind package github

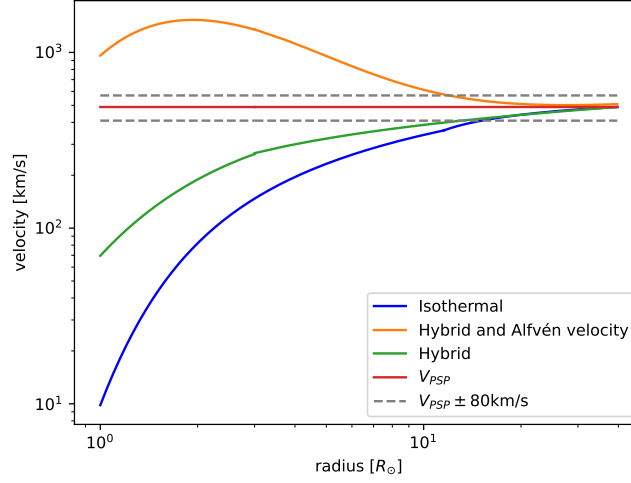


Figure 3.21: Velocity profiles for a certain PSP position and in situ velocity measurement. The blue line corresponds to the implementation of the isothermal profile. The green line is the hybrid profile developed in Koukras et al. [2022]. The red line corresponds to a constant velocity profile with the value of the velocity measured at PSP. The correction interval in dashed lines corresponds to the incertitude intervals usually computed in the literature. The orange line is the profile that corresponds to a hybrid profile, which includes the local Alfvén velocity profile.

$$B(r) = B_0 \left(\frac{r_0}{r} \right)^2. \quad (3.18)$$

Then, the Alfvén speed V_A is determined by:

$$V_A = \frac{B}{\sqrt{\mu_0 \rho}}. \quad (3.19)$$

An estimation of the local density is given by the model by Collier et al. [2001]:

$$\rho(r) = \rho_0 \exp \left\{ -\frac{1.15 \times 10^7}{T} \left(1 - \frac{r_0}{r} \right) \right\} \quad (3.20)$$

assuming an isothermal hydrostatic two-fluid model.

Then, I use reasonable values for T , ρ_0 and B_0 : $T = 1.6 \times 10^6$ K, $\rho_0 = 1.7 \times 10^{-12}$ kg m $^{-3}$ and $B_0 = 1.3 \times 10^{-3}$ T [Collier et al., 2001]. The model results for the above parameters, which also include the acceleration profile, are presented in Figure 3.21 in orange.

As discussed in the description of the connectivity procedure in Section 3.3.2.2, the usual constant profiles are computed at the local velocity at the spacecraft, with variations of ± 80 km s $^{-1}$ around the local value. The velocity profiles are used to determine the equivalent propagation time. Thus, one could apply a constant profile to estimate the propagation time that would match the propagation time using an acceleration

profile. Using the hybrid profile of Koukras et al. [2022], the propagation time is found equivalent to the one calculated with a constant profile at $v_{S/C} - 80 \text{ km s}^{-1}$. Now, if we want to include the propagation of Alfvénic structures in the solar wind, we consider a profile that includes both the acceleration of the solar wind and the local Alfvén velocity. This corresponds to the orange profile of Figure 3.21, which is equivalent in terms of propagation time to a constant profile at $v_{S/C} + 80 \text{ km s}^{-1}$. This justifies the values found in the literature [e.g., Panasenco et al., 2020; Bale et al., 2021].

At this stage, we can now estimate the propagation time for the jets, including different velocity profiles to account for the acceleration and the local Alfvén velocity profile. This in turn allows us to compare the time-series of the number of jets with the in situ time-series of the number of switchbacks.

3.4.5 Determination of the time shift between in situ and jets time-series

Now that I have introduced the models that could be used to determine the propagation time, let us find the relevant time shift between the two time series that will enable us to compare them and perform a correlation analysis. Some additional hypotheses are necessary: We assume a purely radial propagation of the jet perturbation and that all jets propagate at the same velocity. Regarding the latter assumption, there is currently no consensus on whether the velocity of the jets depends on their characteristics.

I thus have to estimate the velocity of the solar wind that will define the propagation time more precisely and with more resolution in time compared to the backmapping step presented before, as I consider bins of 1 hour. I tested the velocity with the different smoothing presented for the backmapping step: running average, running median, and running 20th percentile. I choose the running average to follow the decision of the backmapping step. However, there is a relatively large difference between the running average and the running 20th percentile. As an illustration, a difference of 20 km s^{-1} represents a shift difference in time of about 30 minutes when using the constant velocity profile at a distance of $40R_{\odot}$, and 2 h when using the acceleration profiles. For constant profiles, these errors will be blurred in the 1h-bins. However, for the acceleration profiles, this 2 h time lag will be considered in the large delays I test.

The error for constant profiles is directly included in the uncertainty of the 1h-bins, but the 2 h error should be considered. Then, I compute corrections of the velocity to test this hypothesis, as applied in the backmapping.

The events were processed from the start time of the jets to the measurement of the solar wind at PSP. I first create a list of timestamps with a point every ten minutes that should cover the full corotating interval. For each time in that list, the position of the spacecraft is generated to retrieve its distance to the Sun. Then, I calculate the ballistic propagation time. Finally, I can deduce the emission time for each entry in the list of PSP times. That gives a new list of times that relate the emission time to the time of the in situ measurement.

However, fluctuations of solar wind velocity, associated with an increasing (or de-

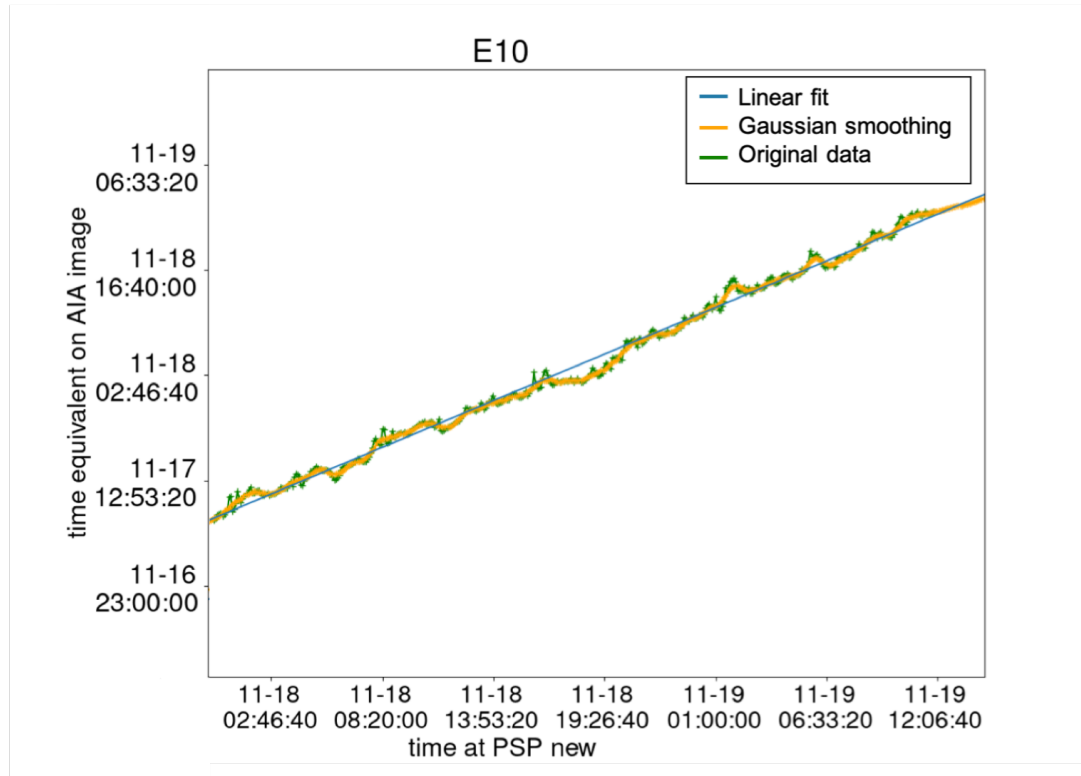


Figure 3.22: Corresponding [AIA](#) emission time for the measurement time at [PSP](#) location. The green crosses are the exact emission time from the velocity median measured at [PSP](#). In orange is the smoothing of the times to remove the variability due to local velocity fluctuations. In blue is the linear fit that allows for unique equivalence between the measurement time and the emission time in [AIA](#) images.

creasing) radius depending on the corotation interval, cause time warping, which can give rise to multiple in situ measurement times that could correspond to the same emission time at the Sun. This is a serious issue when comparing the time-series. To overcome this, we performed a linear fit of the time at the Sun in an attempt to reduce the effect of fluctuations. A linear fit was made on the data so that one emission time corresponds to one PSP time. A simple Gaussian smoothing was not enough to remove the fluctuations. The three steps are presented in Figure 3.22. In green is the estimated emission time from the velocity median measured at PSP. In orange is the Gaussian smoothing of the times to remove the variability due to local velocity fluctuations. In blue is the linear fit of the data that allows for a unique equivalence between the measurement time and the emission time in AIA images.

At this stage, we have an estimation of the measurement times at PSP for each emission time for AIA images, with a cadence of 10 minutes. Let us now determine the beginning and end of intervals in PSP time-series corresponding to the 1-hour interval of the counts I performed in AIA images. The intervals in PSP time-series do not have exactly a duration of 1 hour. That is due to the warping of time, as mentioned before. For the E10 case, the duration of one PSP bin is on average 50 minutes, while it is on average 1h10 minutes for the E15 case.

Now, I have all the constraints set to allow for a comparison of PSP time-series of switchbacks count with the AIA time-series of jets count.

3.5 Results

Let us now concentrate on the results, part of which is presented in the peer-reviewed article Bizien et al. [2025]. As mentioned before, we shall concentrate on two periods only, when PSP was close to perihelion and corotating with the Sun. They are cases 19 and 30 of Table 3.1. Both provide an unambiguous connectivity between PSP and the Sun, with the possibility to visually identify the jets in the source region. For each case, I will first start by showing the connectivity result and then introduce the in situ data and jets identified in EUV images used for the correlated analysis of switchbacks and jets. All the timings in this section are in UTC.

3.5.1 Connectivity during E10

The outbound corotating interval of E10 occurred from November 18, 2021, at 00:00 to November 19, 2021, at 12:00 at PSP [Shi et al., 2022]. The back-mapping time estimation gives a corresponding interval at the Sun starting from November 17, 2021, at 11:00 to November 19, 2021, at 00:00. This is performed at constant velocity.

PSP is connected with a CH, shown in Figure 3.23 in an AIA 193 Å image. The negative polarity at the photosphere matches the polarity observed at PSP (radial magnetic field on Figure 3.24). The different colored crosses are the projection of PSP onto the different source surfaces, with the different lines showing the multiple velocity calculations. The connectivity analysis aligns with the results of [Badman et al., 2023],

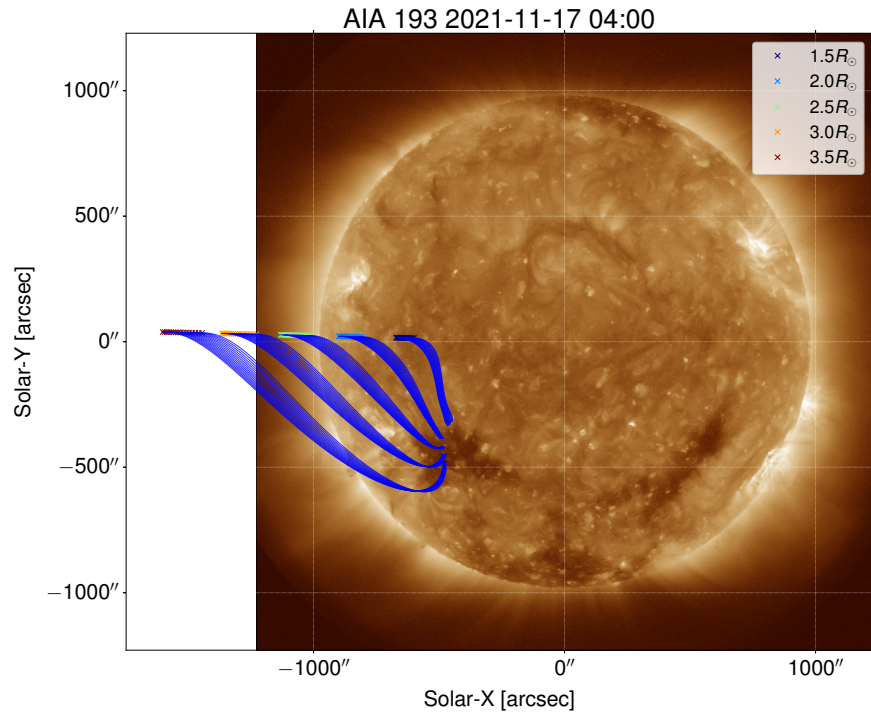


Figure 3.23: The E10 connectivity is shown with a context AIA 193 Å image taken at the same time as the computed extrapolation model with overplotted blue-colored magnetic field lines extracted from the PFSS model, computed at different source surface heights. The colored cross markers are the projection of PSP on the different source surfaces. The multiple field lines correspond to different velocities. All field lines are rooted in the same low-latitude coronal hole. Reproduced from [Bizien et al. \[2025\]](#).

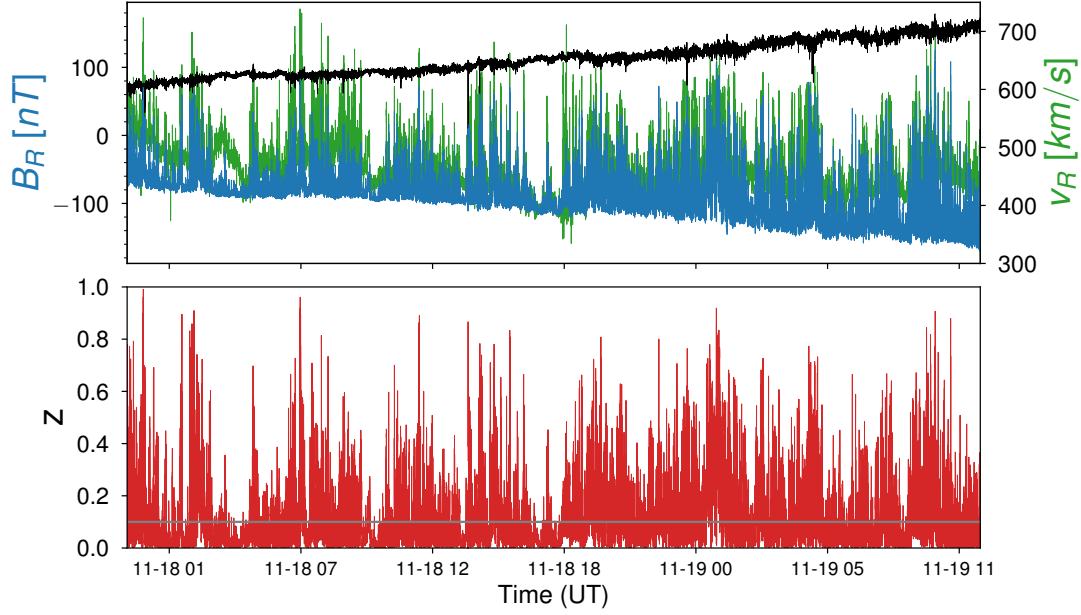


Figure 3.24: In situ [PSP](#) data for E10 for a constant Carrington longitude. The top panel shows the radial magnetic field in blue, proton velocity in green, and the magnetic field magnitude in black. The z parameter corresponds to the normalized deflection from the Parker spiral. The gray horizontal line shows the threshold for the counting of switchbacks in the catalog used (see Section 2.2.5 and Figure 2.8). Reproduced from [Bizien et al. \[2025\]](#).

who studied the complete E10 and, more particularly, the interval we consider. This would indicate the robustness of the methodology. The connectivity of all field lines gives the same source region, which is not affected by the different velocity profiles. However, the different heights of the source surface result in different subregions in the [CH](#) with varying latitudes, shown in Figure 3.23. They are also visible in the region considered for the jet counts in Figure 3.25.

Figure 3.24 shows the in situ measurements of the solar wind magnetic field and proton velocity at [PSP](#) during the corotating interval. This interval corresponds to a fast wind, which matches the expected properties of a solar wind escaping from a [CH](#), and thus gives stronger confidence in the connectivity. I found 508 switchbacks that match the selection criteria mentioned in Section 3.2.1 and Chapter 2, with in particular a minimum deflection of 36° .

[PSP](#) is connected to the same region for the entire corotation period. The latitude range calculated due to the source surface height, on the eastern part of the [CH](#), is the region investigated for the [CBP](#) eruptions. Then, for each interval of 1 h, I mark the location of the base of the jet, using automatic detection to facilitate visual identification (as in Figure 3.20). To show the temporal evolution of the jets, as they do not occur at the same time, they are color-coded with the starting time in Figure 3.25.

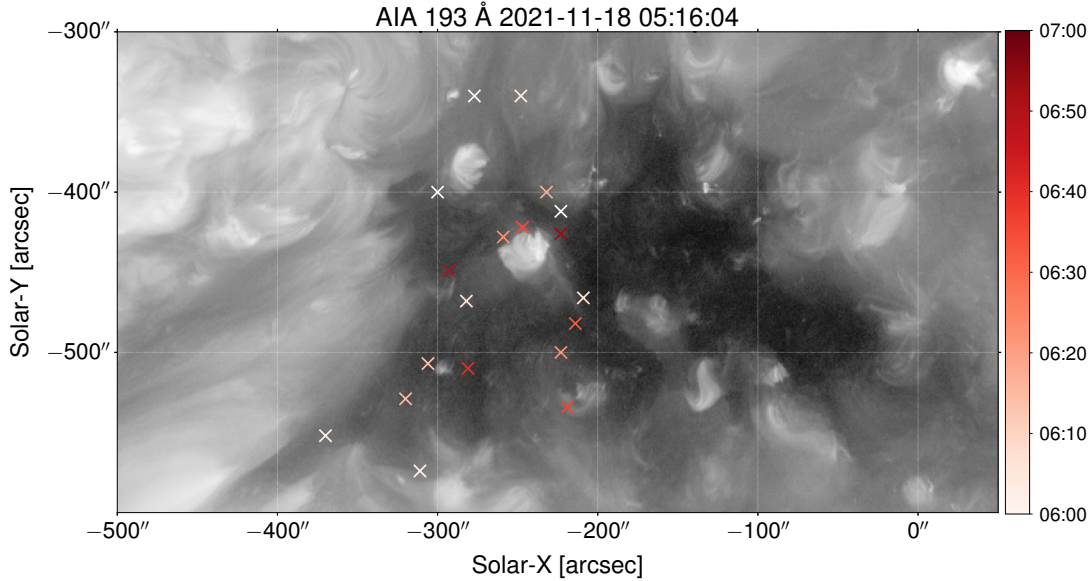


Figure 3.25: Zoom into the coronal hole connected to PSP during the entire corotating interval, with the CBP jets detected during a 1-hour interval. Reproduced from Bizien et al. [2025].

The jets marked on this figure correspond to the jets counted during a 1-hour interval starting on November 18, at 06:00. Table 3.2 indicates the jets identified during this interval. It corresponds to the jets marked in Figure 3.25. I consider the same sub-region of the CH for all 1-hour intervals. The jets I identify have a minimum base size of $3''$ (2.17 Mm) and a minimum duration of 3 min.

Considering the global PFSS model computed around the CH (see Figure 3.26), an open field is found in a region larger than the one inside the boundaries of the CH. It is directly clear that all the CBP jets that I consider are included in this open-field region. However, at higher altitudes, because of the expansion, these field lines may not be connected to the spacecraft as in Figure 3.23. This suggests that we overestimate the number of jets that could reach the spacecraft. However, the perturbations from this region may reconnect, outside the box of the PFSS, to the field line connected to PSP. Thus, we do not exclude jets from the counting due to the limited knowledge of the propagation behavior of the jets.

3.5.2 Connectivity during E15

The outbound corotating interval E15 occurs from March 20, 2023, at 00:00 to March 21, at 12:00. The corresponding solar interval starts on March 19, 2023, and ends on March 20. The connectivity of the spacecraft with the Sun is within a small CH near the solar limb, near an AR (NOAA 13252 noted two days earlier) as presented in Figure 3.27. The CH polarity is positive, matching the polarity at PSP. Neither the back-mapped input velocity nor the source surface height influences the connectivity,

Table 3.2: Table of jets identified during the interval 2021 November 18 from 06:00 to 07:00 of E10. The location and time of the jets' start are indicated. These correspond to the jets marked in Fig. 3.25 for illustration. Reproduced from [Bizien et al., 2025].

Jets	Location [X,Y] in arcseconds	Start (UTC)
1	[-300,-400]	06:00
2	[-277,-340]	06:00
3	[-223,-412]	06:00
4	[-311,-574]	06:01
5	[-370,-552]	06:02
6	[-248,-340]	06:04
7	[-209,-466]	06:06
8	[-282,-468]	06:07
9	[-306,-507]	06:14
10	[-320,-529]	06:15
11	[-232,-400]	06:18
12	[-259,-428]	06:23
13	[-223,-500]	06:23
14	[-214,-482]	06:33
15	[-247,-422]	06:35
16	[-219,-534]	06:36
17	[-281,-510]	06:40
18	[-293,-449]	06:50
19	[-223,-426]	06:54

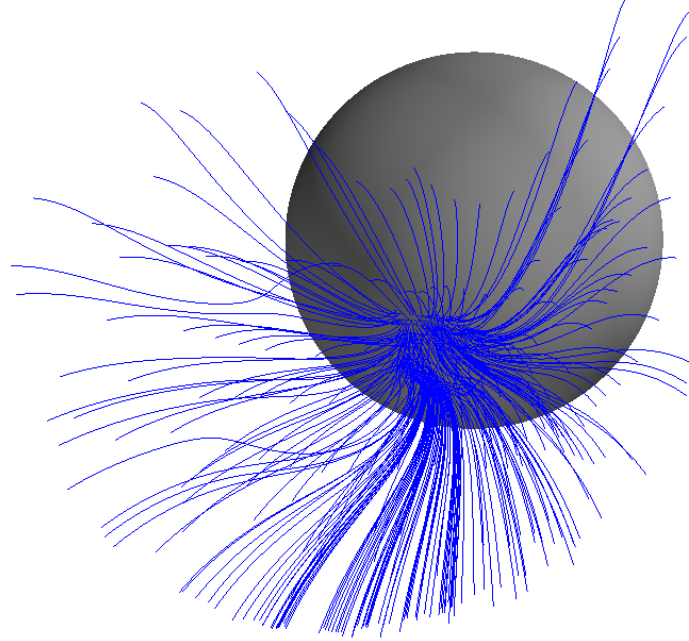


Figure 3.26: Encounter 10 global connectivity, with only the open field lines traced. The observer view is the view from the spacecraft SDO, to allow for comparison with the Figure 3.23.

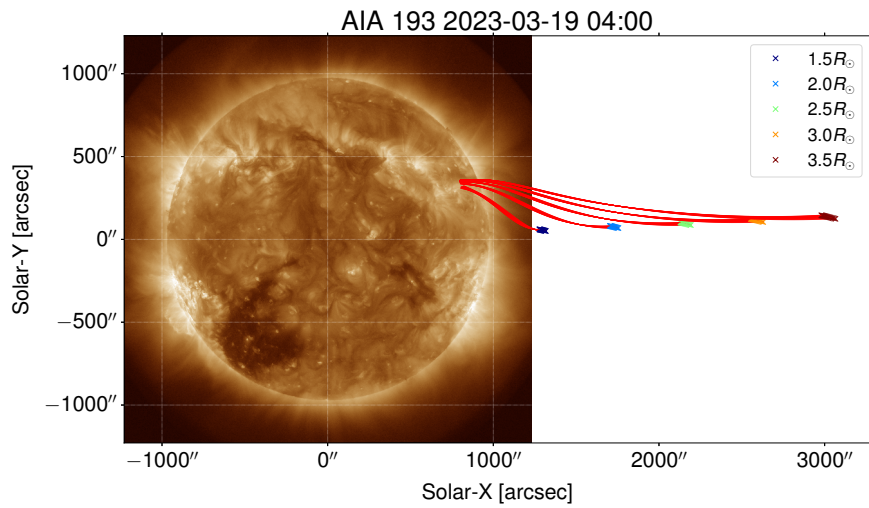


Figure 3.27: Same as Figure 3.23 but for E15. PSP is connected at the beginning of the corotating interval within a small CH near the solar limb near NOAA 13252, as noted two days earlier. Reproduced from Bizien et al. [2025].

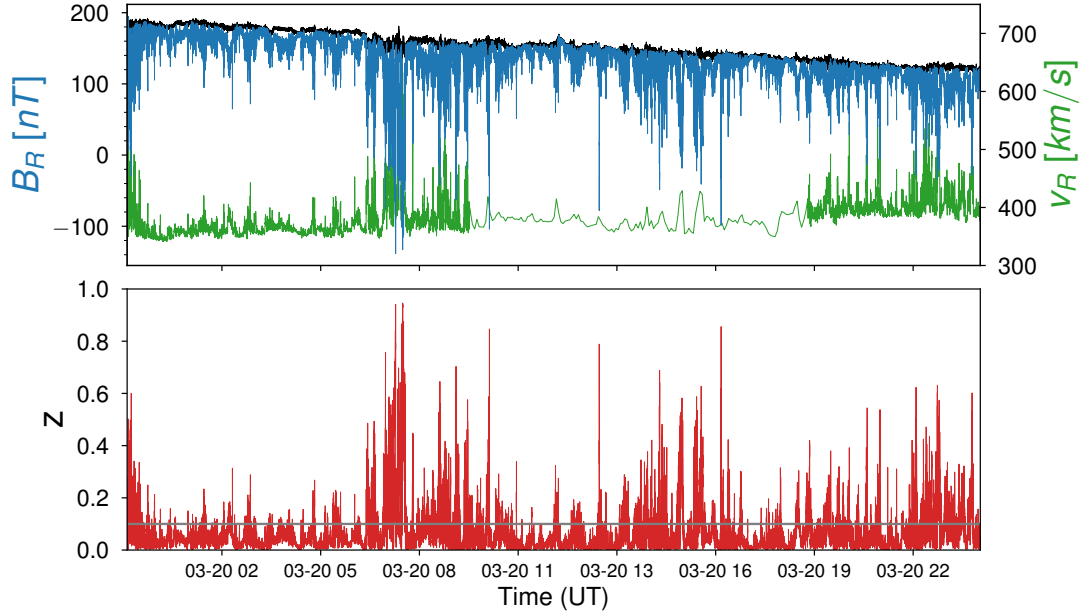


Figure 3.28: Same as Fig. 3.24 but for E15. The interval with lower resolution is due to the limitation of the data allocation, while it can still be used to estimate the propagation time [K. Paulson, private communications]. Reproduced from Bizien et al. [2025].

giving stronger confidence in it.

Figure 3.28 shows the in situ measurements at PSP during the corotating interval. The level of activity is lower compared to E10, as I detect only 82 switchbacks during this interval, with fewer large deflections. The solar wind velocity is slower, about 400 km s^{-1} , which is typical for an AR boundary.

I consider the jets escaping from the CBPs in the region connected to PSP. Figure 3.29 shows the count of jets during a 1-hour interval starting on March 20, 2023, at 01:00, with the same principle as in Figure 3.25. Table 3.3 indicates the jets during the interval of March 20, 2023, from 01:00 to 02:00 of E15. It corresponds to the jets marked in Figure 3.29.

Figure 3.30 shows the global PFSS extrapolation for the open flux region connected to PSP during the corotating interval. Similarly to the E10 case, the footpoints located in the CH expand to cover a wide range of latitudes at the outer boundary of the PFSS. Although case E10 shows a possible large spatial variability in the region considered for events counts using the PFSS, this present CH is relatively smaller and shows only two CBPs in the CH, limiting the risk of overestimating the source region.

3.5.3 Jets and switchbacks occurrence rate comparison

One striking observation is that there is a matching level of activity for the two cases: for the E10 case, with connectivity to a large CH, shows a high level of activity in jets,

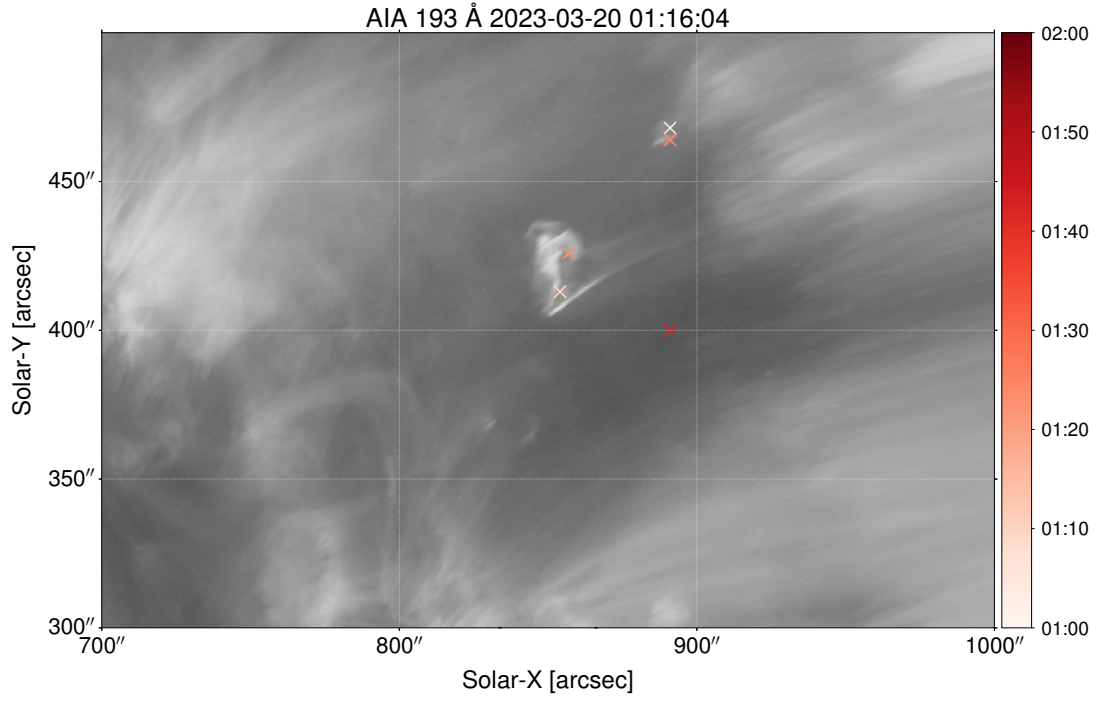


Figure 3.29: Same as Fig. 3.25 but for E15. PSP is connected at the beginning of the corotating interval to a near-limb small CH. Reproduced from Bizien et al. [2025].

Table 3.3: Table of jets identified during the interval 2023 March 20 from 01:00 to 02:00 of E15. The location and the time of the start of the jet are indicated. These correspond to the jets marked in Figure 3.29. Reproduced from Bizien et al. [2025].

Jets	Location [X,Y] in arcseconds	Start (UTC)
1	[891,468]	01:08
2	[891,464]	01:25
3	[857,426]	01:23
4	[854,413]	01:11
5	[891,400]	01:43

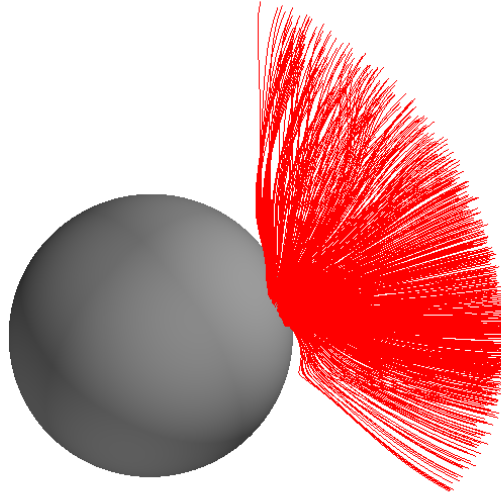


Figure 3.30: Encounter 10 global connectivity, with only the open field lines traced. The observer view is the view from the spacecraft [SDO](#), to allow for comparison with the Figure 3.27.

with an estimation of 649 jets per day and a high level of activity in switchbacks, with 346 switchbacks per day. In contrast, the E15 case shows a lower level of activity, with 79 jets per day, and 142 switchbacks per day, which is relatively lower than for E10. In fact, the *CH* of E15 ($\simeq 10 \times 5$ Carrington degrees) is also smaller than the *CH* of E10 ($\simeq 15 \times 15$ Carrington degrees).

Another interesting observation is that the jetting activity is strong enough to produce all the switchbacks for E10 but not for E15. This observation is important because it has often been used as an indication that the eruptive events investigated can indeed be the source of switchbacks. Jets were found to be insufficient to produce switchbacks [[Huang et al., 2023b](#)], while smaller jet-like structures (jetlets, picojets, etc.) are more numerous and may indeed be as numerous as switchbacks [[Raouafi et al., 2023](#); [Chitta et al., 2023](#)]. That being said, one should be extremely careful in comparing the two rates in absolute terms because so many factors can affect what is occurring between the lower corona and the solar wind. That leads to the discussion about the correlation that I expect and find in such conditions. Currently, there is no proof that one switchback may be produced by a single event. That is why the above-mentioned numbers are given for a rough estimation of the level of activity and not for exact comparison purposes.

3.5.3.1 Encounter 10: High level of activity

Figure 3.31a shows the time-series of the identified eruptive events compared to the switchbacks for E10. The hourly counts of jets identified in the subregion from Novem-

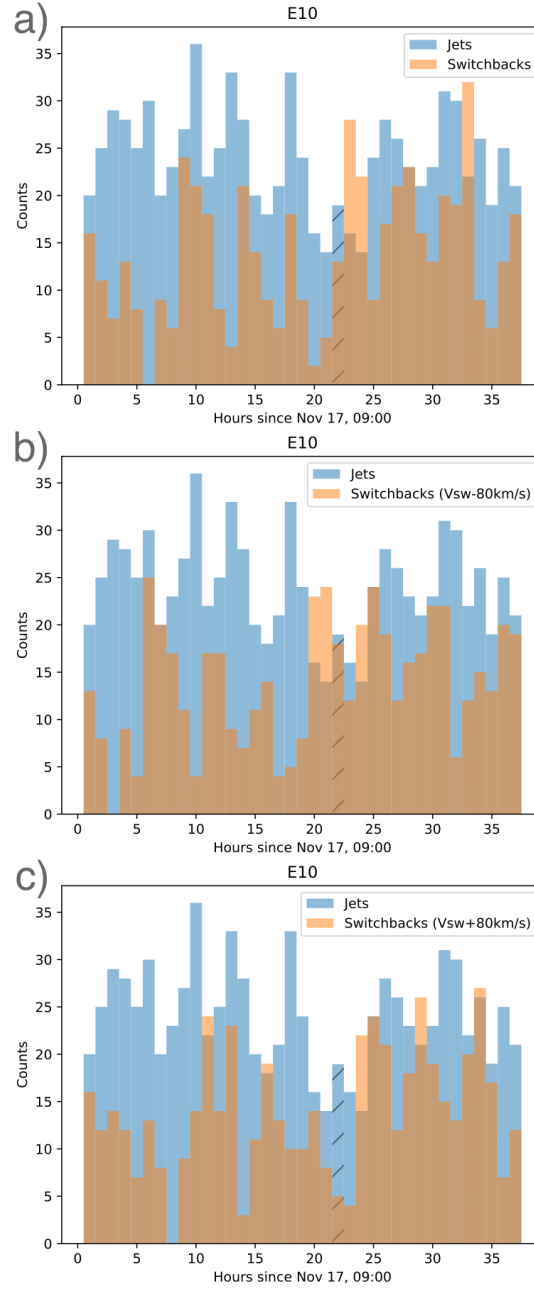


Figure 3.31: Histogram plot of jet and switchback counts. The hourly counts of jets are shown in blue color. The corresponding counts of switchbacks are given in orange. The reference time corresponds to the jet start counting. One bin is highlighted and corresponds to the counts of Figure 3.25. a) E10 counts with constant velocity. b) E10 counts with acceleration correction. c) E10 counts with acceleration correction and Alfvén velocity. Each switchback bin, which is equivalent to the 1 h interval of eruptive events, corresponds to counts over 50 min. Reproduced from Bizien et al. [2025].

ber 17 at 09:00 to November 18 at 22:00 are shown in blue. First, a constant velocity profile is used as a first approximation to estimate the travel time of the eruptive events, excluding the wind acceleration. To investigate the importance of this assumption, I will consider the influence of the acceleration in the next steps of our analysis as explained in Section 3.4.4. For the number of jets and switchbacks, I obtain a Pearson's correlation coefficient of 0.05 (statistically not significant), which suggests that there is no relation between the two time-series. This may be expected because the computed velocity was set relatively high, resulting in an unrealistically fast propagation of the solar wind.

Since the propagation velocity is a critical parameter that influences a back-mapping time and the comparison of the two datasets, let us investigate when we apply a lower velocity to account for the longer propagation time associated with the acceleration profile. That would assume that the jets have an acceleration profile similar to that of the solar wind. As presented in Section 3.4.4, different acceleration profiles can be used. Here, we are interested in the estimation of a propagation time, so we can estimate a constant profile that would match the propagation time corresponding to the acceleration profile. A correction of -80 km s^{-1} is typically used, and I find that it matches simple acceleration models [e.g., Koukras et al., 2022] (see Section 3.4.4). The resulting histograms, presented in Fig. 3.31b, show an anti-correlation with a Pearson's correlation coefficient of -0.42 (significantly different from 0). It is interesting to observe that the computed velocity has a large impact on the estimation of the link between jets and switchbacks occurrence rates. However, as stated in Section 3.4.5, the acceleration profile is more sensitive to local variations of velocity, with larger error bars on the applied shift.

Next, let us assume that the perturbations are carried in Alfvén waves produced during the jets [Lionello et al., 2016], which are directly linked to the Alfvénic properties of the switchbacks [Kasper et al., 2019]. We thus include the Alfvén velocity in the computation of the propagation time. I find that this is equivalent to adding 80 km s^{-1} to the constant velocity (see Section 3.4.4). The results with acceleration, including the local Alfvén velocity, are presented in Figure 3.31c. The correlation test gives a Pearson's correlation coefficient of 0.03 (statistically not significant). Here again, there is no evidence for a correlation.

3.5.3.2 Encounter 15: Low level of activity

Figure 3.32a shows the comparison of hourly counts of jets and switchbacks counted for E15. The method used to superpose the two bar plots is the same as for E10. As for E10, there is no apparent linear correlation, with a Pearson's correlation coefficient of -0.10 (not statistically significant). When including the correction of the acceleration profile, as in Fig. 3.32b, the correlation test gives a Pearson's correlation coefficient of 0.44 (statistically significant). For the test case, which accounts for the acceleration profile and the local Alfvén velocity in Figure 3.32c, the correlation is similar to the constant case with a Pearson's correlation coefficient of 0.18 (not statistically significant).

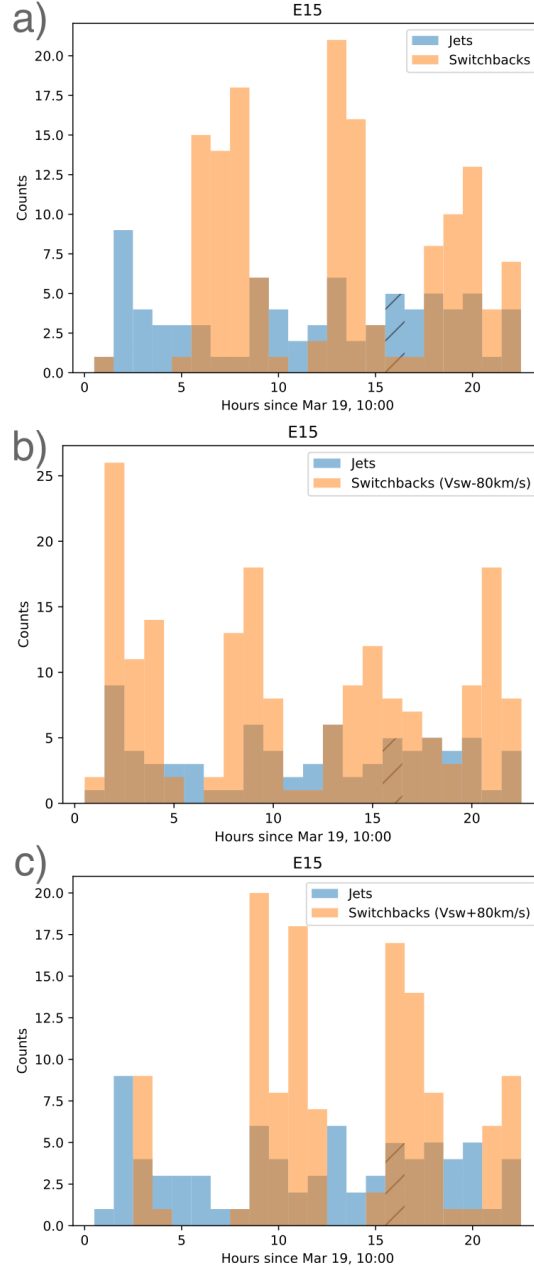


Figure 3.32: Same as Figure 3.31 but for the E15 case. The highlighted bin corresponds to the counts in Fig. 3.29. Each switchback bin, which is equivalent to the 1 h interval of CBP eruptions, corresponds to counts over 1h10m. Reproduced from Bizien et al. [2025].

3.5.3.3 Combined interpretation

These results indicate that the level of correlation depends on the assumed velocity profile, leading to a relative shift between the two time-series. I also tested various intermediate velocities, none of which dramatically changed the level of correlation, with Pearson's correlation coefficients close to 0. The range covered all velocities in the interval $\pm 80 \text{ km s}^{-1}$, extended symmetrically around the mean velocity at PSP, with equally spaced test velocities every 20 km s^{-1} .

The E10 case never shows significant evidence for a positive correlation, while the E15 case might. The reasons could be attributed to the E10 case involving different conditions (e.g., a larger CH), which leads to a larger spatial dispersion of the switchbacks and therefore to a lower correlation. However, the correlation coefficient should be interpreted carefully in deriving firm conclusions on the jets studied here as possible precursors of switchbacks.

Interestingly, one could analyze the level of correlation with the objective of determining which physical processes should be investigated, between the bulk solar wind or the propagation at the Alfvén velocity. However, the level of uncertainties in the overall procedure to connect both time-series may directly impact the investigation of a correlation, which would hide the effect of the physical process considered. It is then impossible to conclude from the investigation on the model to use and thus the propagation processes. Recent results showed an apparent connection between jets and a cluster of switchbacks [Hou et al., 2024a]. They considered the same reasoning for the propagation time of jets, adding the local Alfvén velocity to the bulk solar wind. They found that the difference between the constant profile and the Alfvén-corrected acceleration profile leads to a 1-hour uncertainty. The uncertainty in that case fell in the same cluster of switchbacks, which allowed them to conclude on the causal connection. However, it is unclear what bulk velocity they consider and the level of uncertainty that the bulk velocity brings in the determination of the source region.

A visual inspection of Figures 3.31 and 3.32 strongly suggests the presence of visually similar patterns. The patterns are related to the high variability of the number of jets and switchbacks, with intervals of high activity followed by intervals of lower activity that could even be an interval without activity for the switchbacks. We must also note that we observe significant temporal variability in the number of jets from the same region, which is also evident in the occurrence of switchbacks, potentially linked to switchback patches [Fargette et al., 2021]. This highlights the often overlooked temporal variability of in situ switchback properties [Shi et al., 2022]. This variability persists while considering events with smaller deflections.

The similar patterns could indicate that some switchbacks may indeed have been produced during the jet generation. Some switchbacks may not initiate in the lower corona but at larger coronal heights or in situ in the solar wind. Although we observe similar patterns, there is no clear relation between CBP jets and switchbacks that could validate the CBP jets as precursors of switchbacks. In an attempt to verify whether the relation is prevented due to the implemented methodology, I investigate the parts

that may bring sources of uncertainties. First, I may not detect all low-atmosphere events responsible for switchback formation due to event detection limitations caused by instrumental constraints. Second, the different sizes and energetics of the jets and possibly different acceleration profiles of the produced Alfvénic fluctuations may also strongly influence the comparative analysis. Finally, the uncertainties in the evolutionary phenomena that occur during solar wind propagation may also play a considerable role. Some of these arguments are detailed below.

3.6 Discussion

Although several possible sources of uncertainties have been identified, so far, several remain unresolved and need further investigation. In this section, we discuss their potential impacts. These uncertainties tend to be multiplicative, making it very challenging to establish a causal or even statistical connection between the input and the output. Then, I will propose some solutions that could be investigated in future studies.

3.6.1 Magnetic connectivity uncertainties

The critical link in our chain of processes is the connectivity estimation. Here, we made the assumption that the magnetic field is potential and force-free. This is significantly important when considering small-scale, dynamically evolving structures. It is also directly related to the resolution of the magnetograms.

The [PFSS](#) is highly restrictive in the number of events that can be studied with confidence in the estimated source region. Only four cases over 33 provide unambiguous connectivity to a single source region, while the remaining corotation intervals cannot be investigated in the present analysis. This prevents a statistical investigation of the influence of the properties of the source region, which appears to be an interesting aspect of the two investigated cases. However, one could interpret the multiple sources provided by the [PFSS](#) depending on the source surface height as possible sources of perturbations that would mix at larger distances before reaching the spacecraft [[Viall and Borovsky, 2020](#)]. This would greatly increase the uncertainties, as each source would produce jets with different propagation times and behavior. This would further complexify the analysis as any potential signal would be mixed, increasing the noise floor level.

The influence of the fact that I consider only the intervals for which [PSP](#) is in corotation with the Sun is not clear. Indeed, it then may not compensate for the acceleration, which is one of the reasons that allows back-mapping connectivity to provide reasonable connections.

Moreover, when the connectivity is unambiguous, it can only provide a global region to investigate. The definition of the limits of the source region considered for the counting of events then becomes challenging. The subregion I considered for E10 could then be a smaller area of the [CH](#) or a larger region, including the boundary of the [CH](#), thus having a direct impact on the number of jets. Considering the global [PFSS](#) model

computed around the CH (see Figures 3.23 and 3.26), an open field is found in a region larger than the region I considered. For example, an open field is found at the boundary of the CH, where a higher interchange reconnection rate is expected at the boundaries due to open-closed field connectivity in the area. Although it is included in the counts presented in this analysis, the boundary of the CH could actually be connected to the spacecraft and would significantly impact the jet time-series that would be used for the correlation test. The opposite situation could also be considered, as all the open fields in this area may not be connected to the spacecraft.

3.6.2 Complexity of the jetting activity

The jetting activity adds further complexity to the interpretation. One should distinguish the bulk plasma flow from the wavefront that preceded the jet plasma. Some processes discussed below impact only the plasma flow, which should not influence the results of the statistical comparison, as we assume a connection with the waves produced by the jets.

Here, I clarify the processes that should be considered during the jet evolution. The plasma in the eruptive events escapes into the interplanetary space for some jets [Nisticò et al., 2009; Paraschiv et al., 2010; Hanaoka et al., 2018]. There is a large velocity differential along the jet length, with its leading edge being faster than that of the centroid bulk plasma. That directly explains their elongated shapes in the LASCO observations, possibly caused by the effect of gravity [Wang et al., 1998]. However, the fastest component is usually the wave launched by the jet [Cirtain et al., 2007]. In that perspective, the waves produced by the jets may propagate in the solar wind, while the plasma will eventually fall back to the Sun. Indeed, the produced waves are faster and more likely to reach the escape velocity while the plasma propagates at lower velocities.

Some factors could result in an over- or under-estimation of the number of jets in the source region. First, it is highly probable that not all the jets produce waves that escape the corona. Unfortunately, no dedicated observational study has explored this issue, but ongoing modeling studies attempt to understand it. Thus, I may overestimate the number of jets that should have a causal link observed in the in situ time-series. Second, Chen et al. [2015] shows multiple jets that occur at the location of a CBP, which is often observed in CBPs [Madjarska, 2011]. One could discuss the velocity of the additional jets compared to the initial jet, but in the focus on the released waves, the discussion should focus on the hypothesis that all successive jets would also produce a wavefront. Thus, I may underestimate the number of eruptions in the source region. Indeed, it is difficult to distinguish sub-events that should be counted as two separate events. Third, there is also the possibility that I underestimated the number of jets due to the limitation of visual identification in EUV images. For instance, dark jets are reported by Young [2015] without EUV signature due to poor contrast with the background. These are observed in simulations by Nóbrega-Siverio et al. [2023], but it is still unclear about their properties and occurrence and whether they could launch waves. Finally, the propagation behavior of the jets and the waves is not fully

understood, so the different jets could mix in the propagation to form the complex magnetic substructures observed in the switchbacks [Neugebauer, 2012]. That could be associated with the theory of the merging of switchbacks [Agapitov et al., 2022], discussed in Chapter 2. A solution to reduce the level of uncertainty and improve the jets' identification would be to implement automatic detections. This would start from the automatic detection algorithm presented in Section 3.4.3. It should involve a refinement of the pixels identified to single events and techniques to detect recurring jets (see Appendix B for details). However, it is still clear that this is not easy to implement due to the necessity to detect eruptive events and not any coronal brightening, thus it would require further investigation.

3.6.3 Challenge of the hypothesis of CBP jets as switchbacks precursors

The connectivity methodology only provided the location of the footpoints connected to PSP. The first hypothesis is then that the field lines would reconnect by interchange reconnection and allow waves to propagate to PSP to form the switchbacks. The connectivity of the two investigated cases (Cases 19 and 30) is in a CH where the CBPs are surrounded by open fields. However, it is possible that the CBP would never reconnect with the field lines connected to PSP via the PFSS.

I did not find a clear temporal correlation between the number of jets from the source region and the number of switchbacks at PSP. This may indicate that the initial hypothesis is not valid. We still visually observe similar patterns, which could indicate that some switchbacks may indeed have been produced during the jet generation, but then would require additional mechanisms. This joins the claims that no full reversal switchbacks are observed below the Alfvén surface [e.g., Bandyopadhyay et al., 2022; Cheng et al., 2024]. However, these claims are challenged by the definition of subalfvénic flow in the context of a switchback. In fact, it can be somewhat ambiguous and requires caution. The velocity jet associated with the switchback itself is Alfvénic by nature, implying that the flow within a switchback is locally super-Alfvénic by definition. Rasca et al. [2023] detected the presence of switchbacks below the Alfvén surface, although the occurrence rate is lower than outside the Alfvén critical zone. They discuss whether the switchbacks are formed because of local processes that would create a super-Alfvénic wind or whether the switchbacks and the ambient solar wind are due to the formation of a super-Alfvénic flow. The conclusion about the different works may be that there is no direct relation between the occurrence rate of switchbacks and the Alfvén surface, but it could indicate the existence of in situ mechanisms to generate switchbacks.

3.7 Chapter conclusions

We have strived so far to perform a rigorous connectivity analysis between the Sun and PSP and a jet identification approach to explore a possible causal relation between small-scale dynamic phenomena, that is, jets associated with clusters of small-scale

loops (CBPs) and switchbacks. The initial analysis of all available corotation periods revealed a major unexpected result: connectivity to multiple solar source areas, depending on the source surface height. For most cases, multiple regions of open magnetic flux, as given by the PFSS model, could be connected to the spacecraft. In addition, the standard connectivity methodology showed significant limitations, impacting our analysis of small-scale transient events linked to the local opening of the field.

Thus, I only considered those few cases for which unambiguous connectivity could be found. I observed a similar level of activity (jets and switchbacks) depending on the size of the CH connected to the PSP. However, I did not find a clear temporal correlation between the number of jets from the source region and the number of switchbacks at PSP. The event selection may significantly impact the results, depending on the subregion considered and the instrumental capability to detect some jets (such as dark jets). Lastly, the outcome might be influenced by our limited understanding of the evolutionary processes occurring during solar wind propagation.

Taken together, there are many multiplicative uncertainties, and although this does not imply that I cannot test the connection, it cautions us. Therefore, establishing a causal one-to-one connection between solar jets and switchbacks at PSP has not yet been achieved.

The physical phenomenon considered (the bulk plasma flow or the Alfvén waves) influences the results by the mean of the propagation velocity. The shift in time for the correspondence of the time-series has a direct impact on the correlation. There is also a temporal modulation of the switchbacks observed during corotating intervals with the same source region. It shows that the variability of switchbacks has both spatial and temporal components. The similar variability in jets opens new questions, as it is not expected to see a recurrence of jets.

The hypothesis of the CBP jets as switchback precursors is not validated with the current methodology but could be further tested with improvements in the different aspects involved in the present analysis. Some of the possibilities are discussed in the following section.

3.8 Perspectives

3.8.1 Investigation to resolve the ambiguous connectivity cases

The number of cases in which connectivity provides an unambiguous source region is highly limited. This, in turn, limits the size of the sample that can be considered. This study could be expanded further with some possibilities to find a unique source region in the range of source region from the PFSS. I will present different solutions that could be applied, which should probably be combined to validate a unique source.

3.8.1.1 Implementation of more complex extrapolation models

Most of the uncertainties come from the use of a simple connectivity model, the PFSS. More complex models can be applied, such as Non-Linear Force-Free Field (NLFFF),

which does not suppose that the corona is current-free [Wiegmann and Sakurai, 2021]. It results in a singular constant value of the parameter α for each field line. However, this complex model relies on vector magnetograms, which brings an ambiguity in the vector direction due to the line of sight. This could be solved with two observers [e.g., Valori et al., 2022]. Some studies compared the use of NLFFF to the solution of the PFSS [Tadesse et al., 2014], showing that the NLFFF model reconstructs a better estimation of the magnetic configuration than the PFSS model, in the presence of large loops in ARs. However, it is not clear whether the discussion of more complex models would solve the issues of the PFSS.

MHD models could be used to further improve this analysis, as it may bring less uncertainty about connectivity. However, Badman et al. [2023] compared the output of different models, including PFSS and different MHD models for two encounters of PSP (E04 and E10) and concluded that there were no significant differences in the source regions selected. This is supported by previous comparison of the PFSS with MHD models, which provided a similar topology of the large-scale magnetic field [Riley et al., 2006]. One connectivity study has been performed to connect the Solar Orbiter to the source region in Hou et al. [2024b]. However, details regarding the structure of the applied model and its spatial and temporal resolution are not specified. However, the model retrieved from Predictive Science Inc., “MHDweb”, could be studied in detail to justify the correct estimation of the source region.

Moreover, MHD models require much more computational power, most of the time with lower resolution than the PFSS. This main limitation of the MHD models should be overcome before implementing such a strategy for the connectivity step. New models are currently being developed and could be used for backmapping, as they allow for fast converging solutions. Kennis et al. [2024] shows that the coronal model COCONUT [Perri et al., 2022] associated with the Heliospheric model EUHFORIA [Pomoell and Poedts, 2018], could provide results equivalent to PFSS solutions, in terms of the determination of the open-field regions, while allowing further development.

Some machine learning techniques are currently being investigated to improve the output of extrapolation models [Jarolim et al., 2024]. These models are mostly applied to ARs for the moment and it is not clear how well it would perform for global extrapolations.

3.8.1.2 Extrapolation of the radial component of the magnetic field

The PFSS model provides a value of the extrapolated magnitude of the magnetic field along the field line. One way to validate the connectivity would be to investigate whether the magnitude of the photospheric field, when extrapolated to the spacecraft location, could match the in situ magnetic field magnitude. One could estimate that the field magnitude follows the $1/r^2$ law and compare the value with the in situ measurements. However, this $1/r^2$ model may not match the local evolution of the magnetic field, more particularly to the lower source surfaces. It would require more precise models of the evolution of the magnetic field out to the spacecraft. If such models are

applied, it may allow the removal of certain source regions considered if the extrapolated field magnitude does not match the measured magnitude at PSP. One issue with this strategy is determining which magnetograms provide the best estimation of the magnetic strength at the photosphere. From Figure 3.11, one can see that the magnetic strength is not equivalent between GONG and HMI measurements. The final conclusion about these tests is that they are not constraining enough as very different topologies may lead to the same radial magnetic field component.

3.8.1.3 Composition measurements

As discussed above, the impossibility of attributing a unique solar source could also indicate that streams with different origins would interact outside the lower corona and thus at larger distances to form the solar wind measured at PSP. In such cases, in situ composition measurements could be used to constrain the connectivity by comparing the source region composition with the in situ composition. This strategy has been applied in other studies [e.g., Yardley et al., 2024; Rivera et al., 2024a]. Helium measurements, which are the only composition data that can be retrieved from PSP instrumentation, can be used to infer plasma conditions at the source regions. The solar wind with a high abundance ratio (ratio of the number density of helium to that of proton) originates from a region of the open magnetic field, while low abundance ratios are associated with regions with closed magnetic fields. However, Huang et al. [2023a] found both populations within switchbacks, which may indicate that there is temporal variability in the source. This suggests that it is difficult to conclude on the nature of the solar regions that are connected to the switchbacks.

Other composition studies could be considered with the use of instruments on board Solar Orbiter [Müller et al., 2020], the European Space Agency (ESA) spacecraft which orbits the Sun, since Solar Orbiter is better equipped with composition measurements and allows for a coordinated campaign. Solar Orbiter measurements of slow solar wind composition have been associated with a source region with more confidence than the connectivity alone [e.g., Baker et al., 2023; Yardley et al., 2024]. A proper study would require a corotation of PSP with the Sun, together with the radial alignment of PSP and Solar Orbiter on the same Parker spiral, which is extremely rare. One would first have to validate that the two spacecraft probe the same plasma parcels, including the propagation time between the two spacecraft. This has been performed by Rivera et al. [2024b], who trace field lines from the solar surface to PSP and then to the Solar Orbiter to study the radial evolution of the heating and acceleration of the solar wind. Rivera et al. [2024a] applied this strategy to E11 of PSP with the source region estimated with the PFSS computed at $2.5 R_{\odot}$. They concluded that the switchback composition in heavy ions does not differ from the background composition. However, they detected variability in the composition of Fe/O within and between patches of switchbacks. They proposed that this could be due to a combination of distinct sources, with a mix of potential sources in the QS and others in CHs as it is close to the typical values they deduced. The coordinated composition measurements may be limited in the future due

to technical issues with the Heavy Ions sensor on board Solar Orbiter.

3.8.1.4 Comparison with white light images

As a way to validate our connectivity on a larger scale, one could compare the global magnetic configuration given by the PFSS with white-light images showing streamers and pseudostreamers. Indeed, white-light images offer powerful constraints to the large-scale topology of the coronal magnetic field from the limb to 6 solar radii, in the case of solar eclipse images [Boe et al., 2020]. Interestingly, the latter found that the field becomes radial at distances larger than the one assumed in the PFSS extrapolations, between 4 and 5 $R_{\odot}$.

This strategy of using white-light images during eclipses has been applied in Benavitz et al. [2024], with the aim of determining the source surface height. They find that lower source surface heights are better suited for solar maximum, while higher source surface heights provide better estimation at solar minimum.

Unfortunately, solar eclipses are too rare to validate our connectivity. The rarity of eclipses is the reason behind the development of coronagraphs (see Chapter 1). The most convenient instrument is currently the LASCO C2 coronagraph [Brueckner et al., 1995], on board the SOHO spacecraft [Domingo et al., 1995]. The telescope is designed to block light coming from the solar disk in order to see the extremely faint emission from the region around the Sun (see Chapter 1). It provides a view of the solar corona from about 2.5 to 4.5 solar radii for the C2 instrument. The white-light images mostly show the field lines in the plane-of-sky, with a small component in the out-of-plane direction. The intensity is associated with Thomson scattering [Howard and Tappin, 2009], which is a special case in the general theory of the scattering of electromagnetic waves by charged particles. The main idea is that when the waves interact with an electron, the electric field of the waves accelerates the electron in a plane perpendicular to the direction of propagation of the wave. Then, depending on the position of the observer, polarized or unpolarized light will be observed.

I contacted Huw Morgan [Aberystwyth University, UK], who provided me with the LASCO-C2 images corrected of the stray light patterns. This correction is not applied on the open access available data⁶. Figure 3.33 shows an example of the corrected image of the C2 coronagraph. The bright features correspond to the extension of the coronal streamers, with a higher plasma density.

To start with, one could look at the coronal magnetic structures that should appear in the LASCO images. Then, different computations should be performed at different source surface heights. Figure 3.34 shows different outputs of the PFSS computed from the same magnetogram but with different source surface heights. The regions of open field vary extremely between the different panels, as well as the location of the streamers. This may allow us to validate the large-scale magnetic topology.

Synoptic white-light images can be produced from the measurements of LASCO-C2. It can be used to determine the position of the streamer belt, the core of which

⁶<https://lasco-www.nrl.navy.mil/>

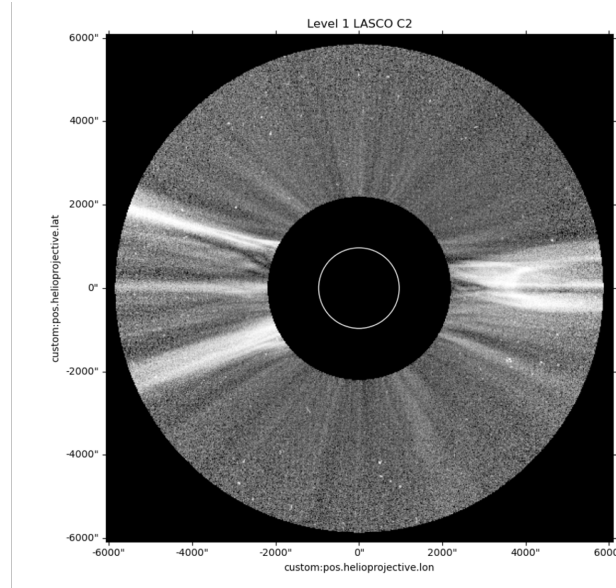


Figure 3.33: [LASCO C2](#) white light image of the solar corona during the period of interest of E10. This image has been corrected for stray light patterns.

can be compared to the [HCS](#) provided in the [PFSS](#) model [[Poirier et al., 2021](#)]. This strategy, implemented in the Magnetic Connectivity Tool, with the comparison of the co-temporal image to the [PFSS](#), could reduce the number of source regions to consider.

Additionally, one could investigate the data from another mission, [STEREO](#), with the coronagraph [COR2](#), part of the Sun Earth Connection Coronal and Heliospheric Investigation ([SECCHI](#)) package. [COR2](#) has better characteristics than [C2](#), in terms of cadence and resolution. An observation campaign was performed during an encounter of [PSP](#), which may be investigated in the seek of the source regions in this current analysis [[DeForest et al., 2018](#)].

3.8.1.5 The possible limitation of a connectivity analysis

A reasonable question that could be raised at this stage is whether the [PFSS](#) and the ballistic mapping would always provide a wrong connection between the spacecraft and the solar surface. In that case, a methodology similar to what I implemented will never allow to test the hypothesis of the [CBP](#) jets as switchback precursors.

Then we could investigate all the [CBPs](#) from the [CH](#) where it is clear that the open field will allow jets to escape the corona. Including [CBPs](#) from the [QS](#) could be a possibility but would then require further studies to understand the propagation behavior of the jets and their ability to escape the Sun. With a focus on [CH](#), an estimation of the hourly counts of jets could be performed and compared to the in situ time-series. The comparison could be performed by merging all the [CBPs](#) time-series in all visible [CHs](#) or taking the time-series from individual [CH](#). A limitation for this type of work would be to estimate the times to consider for remote observations, including

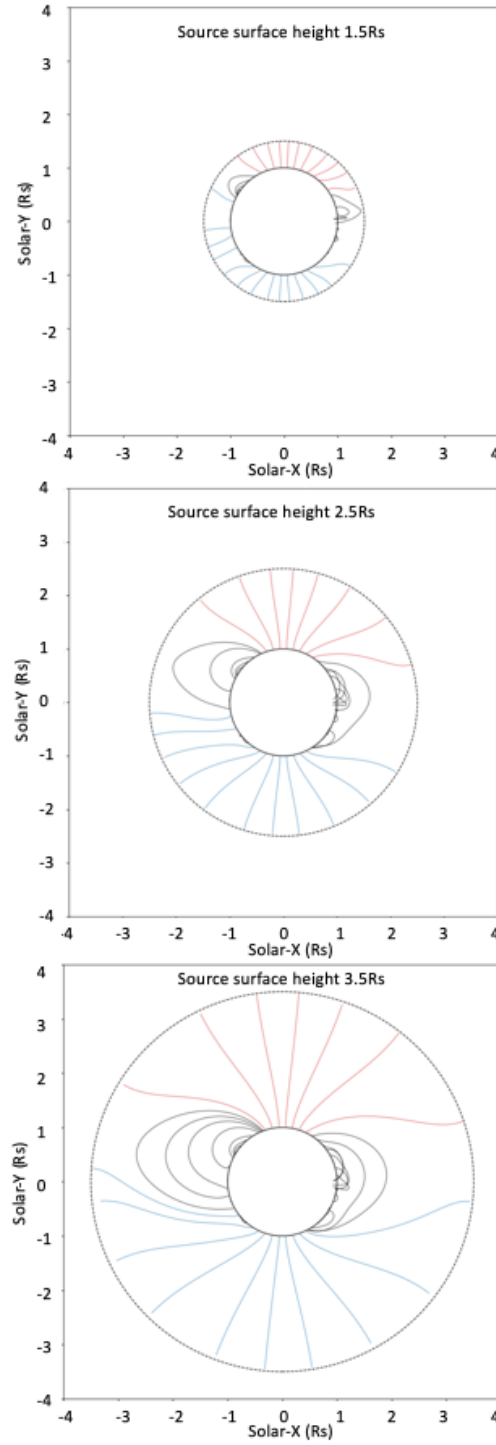


Figure 3.34: Cut of the PFSS in the plane perpendicular to the Sun-LASCO line. The different panels correspond to different source surface height used as input of the PFSS. The top panel height is at $1.5R_{\odot}$, the middle panel at $2.5R_{\odot}$ and the bottom panel at $3.5R_{\odot}$.

only the period when the spacecraft is likely to probe the plasma from these CHs and would not be located on the far side of the Sun.

Another type of investigation would focus on the position of the spacecraft more precisely, with the estimation of the jets that would cross the trajectory of the spacecraft. Using remote observations of jets, [Huang et al. \[2023b\]](#) estimate the number of jets that could be encountered by PSP along its trajectory. That is based on the estimation of the total number of jets on the full Sun at a certain time on EUV images. They find that the occurrence rate of jets, about 0.12 to 0.73 per day, is less than the hundred of switchbacks per day. They conclude that there are not enough jets for them to be the source of switchbacks. However, there is no discussion on the in situ data they consider. According to the number of switchbacks they provide, they likely also include deflection with an angle smaller than 90° since their number is higher than the number of full reversals usually detected. However, this is a supposition, but their conclusion would require the support of in situ measurements. Although this methodology is interesting, taking into account the probability of catching an eruptive event at PSP, it is difficult to use this study as a conclusion on the connection of switchbacks with jets.

At this stage, I proposed different strategies that could be combined to resolve the ambiguous connectivity cases that compose most of the interval of interest. However, the limitation of this work is not only in the connectivity but also in the comparison of transient eruptive events with local reversal of the field measured in situ. I will now discuss what could be attempted to investigate a relation we could expect from the recurring pattern observed in the time-series.

3.8.2 Further tests of the hypothesis of CBP jets as switchback precursors

3.8.2.1 Timing of each jet

One aspect that has a clear influence on the results is the decision to consider 1 h duration bins for the rate of switchbacks and jets. Indeed, considering the uncertainties in the propagation from the solar corona to the spacecraft, a statistical investigation is required for studying the link between jets and switchbacks is not clear. The duration of the bins is a trade-off between the time resolution that is required to resolve the variations in the jet activity and the sample size in each bin, which is required to reduce Poisson fluctuations. Another and better approach would be to compare the sequence of onset times of jets and switchbacks rather than their number in 1-hour bins.

3.8.2.2 Investigation of other parameters

This work shows the complexity of searching for a correlation between switchbacks and CBP jets. Here, I only compare the occurrence rates, which may be too restrictive. Another possibility is to compare the lifetime of the CBP, as well as the duration of

one jet, with the duration of switchbacks in situ. That would only be possible during corotation, where the duration in the time-series represents a temporal scale. I showed that the occurrence of jets and switchbacks is related to the source region, with the size of the CH. Future analyses should focus on determining which other properties of the source impact the switchbacks, not only the occurrence but their properties, such as the level of Alfvénicity or the waiting time between jets and between switchbacks [Lee et al., 2024].

The switchback patches could also be investigated and were one of the first switchback studies to show proof of the solar origin of the switchbacks [Fargette et al., 2021]. Bale et al. [2023] investigate in situ measurements of switchbacks, with the objective of finding markers of their relation with the supergranulation scales. The list of evidence includes an asymmetry of the patches, with initially larger deflections of the magnetic field and relatively smaller deflections at the end of the patches. That would indicate that the magnetic field keeps an imprint on the supragranular cells. When PSP crosses such patches, it then observes this asymmetry as an indicator of the times when reconnection occurred in the low corona. Higher velocity, and thus large angle of deflection (see Section 2.5.4), indicates that the spacecraft crossed field lines that just reconnected, while lower velocity in the same patch is an indication of a field line that reconnected earlier, and the peak of the velocity passed the spacecraft location earlier. When the velocity is at its lowest, it corresponds to the jump from one cell to another cell. While that brings more constraints on the eruptive events we should consider, it does not allow conclusions on the origin of single events.

General conclusions and perspectives

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4.1 Summary

In this thesis, we have addressed two facets of a topic that is currently receiving considerable attention, namely switchbacks, which refer to magnetic deflections, which are ubiquitous in the measurements of [PSP](#). Two non-exclusives group of models have been proposed for their genesis. The first involves an in situ generation in the solar wind and requires specific plasma conditions. The second argues that the switchback precursors are perturbations originating from the low corona through interchange reconnection. This is the context in which my thesis work is set. My aim was to give direct insight into the origin of the structures as well as into the dynamics of the switchback propagation in the solar wind.

Chapter 2 focused on the nature of switchback boundaries. The aim was to verify whether the boundary allows for mass and energy exchange with the ambient solar wind. The boundaries can be considered as classical [MHD](#) discontinuities, i.e. as Tangential and Rotational Discontinuities. The first encounter of [PSP](#) showed signatures indicative of Tangential Discontinuities, in contrast to what previous studies have found. The boundaries may then be considered as closed structures that prevent any exchange of mass and energy across. This supports their stable nature, which could allow them to survive to large distances. The conclusion prevails for all angles of deflection, so that the boundaries nature and thickness satisfy the self-similar nature of the switchbacks. These results are compatible with a solar origin, but we cannot exclude an in situ formation. However, the relation between the nature of the boundary and the radial distance to the Sun is not clear. The thickness of the boundaries exceeds [MHD](#) scales.

It also appears that no thin boundaries are observed far to the Sun, which could indicate the boundaries are not eroded while they propagate.

Following the results of Chapter 2, Chapter 3 presents the investigation on the possible solar origin of switchbacks. I explore the hypothesis of a switchback source in the lower corona by combining in situ and remote-sensing observations, using a rigorous methodology to connect both measurements. A first major result is the difficulty in establishing a clear connectivity with the PFSS, with a strong dependence on the height of the source surface. Focusing on two intervals during which PSP was in corotation with the Sun, I find a matching level of activity between the jets and the switchbacks, depending on the size of the region connected to PSP. I also visually detect similar trends in the number of jets from the estimated source region and the number of switchbacks measured by PSP. However, no significant correlation is found between time-series of the event numbers, unlike the results found by Hou et al. [2024a]. Although this absence of correlation may be related to uncertainties in the connectivity and jets identification, it may also indicate that there are too many processes acting between the jets and the switchbacks, which blurs the correlation, if there is any. Finally, we confirm that the variability of switchbacks rate has both spatial and temporal components, as found by Shi et al. [2022].

4.2 Impact of the thesis

4.2.1 Switchback boundaries

Discontinuities encountered in the solar wind have been extensively studied by many authors [e.g., Mariani et al., 1983; Scudder, 2005; Wang et al., 2024] using the Minimum Variance Analysis (MVA). However, it is surprising to discover that the MVA, applied switchback boundaries [e.g., Larosa et al., 2021; Akhavan-Tafti et al., 2021; Vinogradov et al., 2024] despite its limitations. These limitations caution the automatic statistical interpretations [e.g., Knetter et al., 2003; Wang et al., 2024]. In the specific case of the switchback boundaries, this is even more critical. In fact, the 3D nature of the boundary, with the arc polarization and the superimposed fluctuations that are usually present at the boundaries, prevents the routine use of MVA to determine the boundary nature. The consequence of this is that the blind application of the MVA to switchback boundaries leads to a strong overestimation of the fraction of Rotational Discontinuities.

The Alfvénic nature of the switchbacks is clearly observed in the constant magnitude of the magnetic field, which constrains the rotation of the field vector, and in the correlated fluctuations of the velocity and magnetic component. However, when we relate the properties of the boundaries with the Alfvén velocity and the constraints about the propagation of the boundaries, the boundaries show deviations from the Alfvénicity, as previously detected in the literature [e.g., Larosa et al., 2021; Farrell et al., 2020]. This raises several challenges about the boundaries that should be understood.

First, switchbacks are sometimes considered as the result of the growth of large-amplitude Alfvén waves that can result in a reversal of the field [e.g., Squire et al., 2020].

Thus, one would expect to observe the signature of the Alfvénicity at the boundary, with a Rotational Discontinuity. The perspective of a closed nature of the boundary shows no clear impact on the theory but may constrain the propagation and growth of the Alfvén wave.

Secondly, can the closed nature of the boundaries be reconciled with the propagation of the switchbacks in the solar wind at the Alfvén velocity? A tangential discontinuity does not have a velocity relative to the plasma, so it does not propagate in the solar wind. This is contradicted by observations that show noticeable velocity spikes. Thus, there is no clear solution to the question raised here.

The purpose of determining the nature of the boundary was to understand the likelihood that the switchbacks could be eroded, as several authors showed variations in their occurrence rate with radial distance to the Sun [e.g., [Tenerani et al., 2021](#); [Jagarlamudi et al., 2023](#)]. Future studies should focus on the possible erosion mechanisms at the boundary that may be possible in the presence of a closed boundary and boundaries with relatively large thicknesses in the MHD scales. This includes magnetic reconnection but also surface waves and instabilities that are due to velocity shear, such as the Kelvin-Helmholtz instability.

One of the major challenges about the switchbacks is to understand their 3D nature from the 1D time-series obtained by the crossing of the structure by a single probe. The analysis of the orientation of the boundaries can provide constraints to the geometry of the switchbacks. Most switchbacks have both boundaries with the same orientation. For some events with small deflections, the two planes are not parallel but present a significant angle between their relative normals. In all cases, the boundary plane is mostly parallel to the Parker spiral direction. This information should be combined with the preferential deflection direction in the T direction (from the RTN frame) [[Fargette et al., 2022](#)]. Indeed, the latter showed that the polarity of the magnetic field lines impacts the geometry of the switchbacks.

4.2.2 CBP jets as switchbacks precursors

An extensive examination of the entire set of corotation periods yielded an important result: structures observed by PSP that are seemingly magnetically connected to one single solar region can actually be connected to more than one region depending on the altitude of the source surface. This challenges the results of previous studies that aimed to connect in situ measurements at PSP in an unambiguous way with their solar source [e.g., [de Pablos et al., 2022](#); [Kumar et al., 2023](#)]. This under-looked issue could possibly rewrite our understanding of the solar origin of in situ events, including switchbacks. Indeed, it is possible that all the different sources given by the PFSS produce winds and perturbations that mix and reconnect at larger distances in the corona and in the interplanetary space. This theory is supported by the measurements of abundance ratios, which show the signature of mixed sources [[Huang et al., 2023a](#); [Rivera et al., 2024a](#)].

For the few cases in which unambiguous connectivity could be found between the

source region and PSP, I observed a matching level of activity (jets and switchbacks) depending on the size of the CH connected to the PSP. However, I did not find a clear temporal correlation between the number of jets from the source region and the number of switchbacks at PSP. This result may seem to contradict models involving jets as switchbacks' precursors. It is also in contradiction with the recent study by Hou et al. [2024a].

So far, only a periodicity comparison has been cited to prove the relation between switchbacks and jets [Kumar et al., 2023; Hou et al., 2024b]. However, these studies may not include all the uncertainties that should be considered. Kumar et al. [2023] is using time-series outside the corotation, with the source behind the limb, and shows issues in their analysis, which prevents the cotemporal interpreting of matching periods in the switchbacks time-series and jets in CBP and at the base of plumes. Hou et al. [2024b] included all coronal brightenings, which is one of the warnings I want to raise about their study. A brightening is the result of a change of density or temperature in the lower corona and would not necessarily indicate an eruptive event. At this stage, it is, then, unclear about the existence of such periodicity. If it exists, it would also question the validity of any connectivity analysis and time-series comparison. Indeed, it would indicate that any shift of the switchback time-series with a time lag equal to the period would provide a similar correlation coefficient. Thus, we should first understand the physical reasons why we may observe a recurrence in CBP eruptive events.

Recently, Hou et al. [2024a] claimed to have found a definite relation between 10 jets and 10 clusters of switchbacks. They tested different parameters to validate the connectivity: an interval during approximately the corotation of E04, the source surface height, the white-light comparison, the helium abundance comparison, and the correction of the velocity profile with the Alfvén velocity to compute the propagation. They find an uncertainty of 1-h between the time-series that is relatively small compared to the duration of one cluster of switchbacks. They concluded that jets are the precursors of switchbacks. It is, however, unclear how the uncertainties in the propagation processes may affect their conclusion.

4.3 Outlooks

A general point about the switchbacks is that they were not discovered by PSP, but the omnipresence of the magnetic folds in the first encounter led to their extensive study since the launch of the mission. As they are omnipresent, they might shed light on open questions such as the heating of the corona and solar wind and acceleration of the solar wind. Even if they are not the cause of the phenomenon, they could be a tracer of the evolving dynamics or preserve markers of the events that cause the coronal heating at close distances to the Sun. In situ measurements inside the lower corona are not possible, and the resolution of remote sensing instrumentation and the connectivity models may not allow one to resolve the problem. The aim of the in situ investigation is then to provide the most constraints to models that could simulate a solar perturbation until they form switchbacks as measured at PSP. The end of life of

the switchbacks is also unclear as to whether they disappear or are gradually merged with the turbulent wavefield.

As I was limited by the only two examples correctly determined by the connectivity, I could not investigate the link between the type of source and the in situ properties of switchbacks. However, it is clear from the in situ data that the spacecraft probes different plasma conditions, with fast Alfvénic winds and sometimes relatively slow winds. From that perspective, one should try to compare the source region for the different conditions of wind. Switchbacks are supposed to not survive in the slow wind and quickly disappear. One could investigate these slow wind intervals and look for some remnant switchbacks and, more particularly, to their boundary. It is indeed not clear whether switchbacks are ever created in the non-Alfvénic slow wind or whether they are dissipated before reaching the spacecraft. The slow wind sources should then be investigated, looking for jets. A similar investigation should be performed during intervals for which the spacecraft is below the critical Alfvén surface. The presence of switchbacks below this surface is debated in the community.

Simulations show that intermittent reconnection simultaneously excites three types of MHD waves: Alfvén waves, fast magnetosonic waves, and slow magnetosonic waves [He et al., 2021]. That is interesting from the perspective of a connection between jets and switchbacks. In the analysis presented in Chapter 3, I focused on the discussion on Alfvén waves that would propagate and could, in turn, become a switchback. However, other types of waves could also be investigated as the Alfvénic nature of switchbacks is not always preserved [Larosa et al., 2021; Froment et al., 2021]. Fast and slow magnetosonic waves have been proposed to lead to the compressive nature of the switchback boundaries [Larosa et al., 2021; Chaston et al., 2020].

In search of a link between the small-scale eruptive events and the in situ switchbacks, simulations are developed with a large domain so that they can simulate the propagation from the solar corona to the spacecraft. The models currently implemented to study the propagation of jets to the location of PSP are based on the ARMS code [DeVore and Antiochos, 2008]. Although recent simulations [Roberts et al., 2018; Touresse et al., 2024, Wyper et al., in prep] could be a major advantage in proving the relationship between jets and switchbacks. In fact, the simulations show that the untwisting waves survive to the location of PSP. This emphasizes the necessary investigation of a causal link between CBP jets and switchbacks.

It would be interesting to investigate which type of switchback boundaries they obtain. These simulations could also allow us to understand the 3D structures of the switchbacks. The current understanding of the switchback structure is highly limited and the proposed S-shaped structures are misleading and restrict the interpretation of some of the in situ data. An interesting discussion arises from the position of the measurements along the spacecraft orbit. It could usually be divided into two categories: the corotation interval and the longitudinal sweep that occurs between the two corotation intervals. The inbound and outbound intervals preceding and following the corotating intervals should display a switchback crossing signature similar to that of the longitudinal sweep. It is relatively easy to reconstruct the 2D shape of the

switchbacks if one imagines that the spacecraft cuts the structure almost perpendicular to the boundary [Laker et al., 2021]. One could imagine that this situation prevails during the longitudinal sweep, in which the spacecraft would cross different flux tubes. However, during the corotation intervals, it is more likely that it crosses the structures almost along the elongated direction of the flux tube. One may then expect to observe different signatures in the time-series, with less sharp boundaries. However, the sharpness of the boundaries of the first encounter in the corotation period is clearly observed in the time-series. Statistically, we see a difference in the properties of the switchbacks [T. Dudok de Wit, private communications] during/outside of corotation intervals. One should then perform a statistical analysis of the switchback properties with a differentiation of their position along the orbit.

Then, in the simulation of jets that would evolve into switchback reversals [Touresse et al., 2024, Wyper et al., in prep], we can use the simulations to investigate the impact of the crossing of switchbacks on the properties of the boundaries. One could also imagine that we observe different signatures depending on the crossing, so that we may actually underestimate the number of switchbacks in the timeseries as we would not consider the less clear cases.

Overall, this thesis brings a new understanding of the switchback's ability to evolve in the solar wind but shows the new challenges to investigate to link the switchbacks to the heating and acceleration of the solar wind. It also shows that simple models are still not sufficient to validate the theory of a solar origin of switchbacks, but highlights the path for future studies to resolve the remaining sources of uncertainties, including the limited knowledge of the propagation of transient events that could be solved by numerical simulations.

Résumé en français

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5.1 Résumé du chapitre 1 : Introduction

Nous commençons ce voyage par une exploration de la structure du Soleil, en nous concentrant sur son atmosphère, dont les couches limites sont la photosphère et la couronne solaire. La photosphère est la couche à la surface du Soleil, qui émet dans le visible et est donc observable depuis la Terre. La couronne est quant à elle observable lors des éclipses solaires. Elle est constituée de plasma et de champs magnétiques qui respectent la propriété du « frozen-in ». Le rapport entre la pression du plasma et la pression magnétique, appelé « plasma β », détermine la force dominante entre le mouvement du plasma et le champ magnétique. Dans la couronne, le champ magnétique structure le plasma, dont le flux dans le vent solaire et dans l'héliosphère guide le champ magnétique. La couronne présente ainsi des boucles magnétiques complexes, principalement au niveau de l'équateur (cf. Diagramme papillon), tandis que les régions polaires sont composées majoritairement de champs ouverts, dans des régions que l'on appelle trous coronaux. Bien que l'on s'attende à ce que la température de l'atmosphère diminue avec l'augmentation de l'altitude, la température de la couronne augmente de manière inattendue par rapport à la température de la photosphère. Cela suggère l'existence de mécanismes qui transportent et dissipent de l'énergie pour chauffer la couronne, avec comme source d'énergie les mouvements convectifs de la photosphère. L'étude de la couronne présente des défis en raison de ses courtes échelles de temps, de ses petites échelles spatiales et de ses variations de température, ce qui nécessite des instruments avancés pour une compréhension plus approfondie. Le vent solaire présente aussi un comportement inexpliqué, en raison de son profil d'accélération. L'existence du vent solaire est directement liée à la couronne et ses températures extrêmes. Les phénomènes étudiés pour résoudre ces questions ouvertes sont donc intrinsèquement liés.

Les nombreuses questions qui restent sans réponse ont conduit au développement de missions spatiales en orbite autour du Soleil. Une grande amélioration pourrait être

apportée en envoyant une sonde à des distances proches du Soleil, là où les mécanismes qui chauffent et accélèrent le vent se produisent. C'est l'une des raisons qui ont conduit la NASA à envoyer un satellite, PSP, pour devenir la mission spatiale la plus proche du Soleil [Fox et al., 2016]. Il a été lancé en août 2018 par la NASA. Sa durée nominale est de sept ans, qui sera éventuellement prolongée. La distance minimale au Soleil sera atteinte à la fin de l'année 2024. En décembre de cette année, PSP sera à 9,85 rayons solaires du Soleil.

La première orbite de PSP a révélé dans l'héliosphère interne un vent solaire hautement structuré avec la présence inattendue de discontinuités soudaines. En effet, des fluctuations magnétiques dans la direction radiale mesurées par PSP sont observées. D'après les mesures in situ précédentes et la théorie du vent solaire, on s'attendait à observer de petites fluctuations, comparées à la magnitude du champ magnétique, avec une direction principale centrée autour de la direction radiale de la spirale de Parker. Les nouvelles mesures de PSP montrent l'importance des grandes déviations, de l'ordre de la magnitude du champ, qui peuvent conduire à une inversion complète du champ magnétique. Elles sont omniprésentes dans les mesures de PSP [Bale et al., 2019; Kasper et al., 2019].

La première mention du terme « switchbacks » se trouve dans Yamauchi et al. [2004], pour décrire les structures magnétiques qui semblent se replier sur elles-mêmes. Comment peut-on justifier cette signature d'inversion ? C'est l'une des questions qui devraient se poser directement lorsque de telles conclusions sont basées sur des mesures en un seul point. En effet, les séries temporelles provenant d'un seul satellite ne peuvent à elles seules fournir une compréhension 3D complète de la structure. Une signature magnétique similaire pourrait être observée si le satellite traversait plusieurs lignes de champ de polarité opposée. Cette question peut être abordée par le biais de la population d'électrons énergétiques appelés électrons de strahl. En effet, les données de l'angle d'inclinaison des électrons dans l'intervalle de flux qui correspond au strahl permettent de déduire la topologie locale du champ magnétique et de confirmer l'apparente déflexion du champ.

Une observation intéressante concernant les switchbacks est la corrélation entre les fluctuations du champ magnétique et les pics de vitesse positifs [Kasper et al., 2019]. Cette propriété, observée dans le vent solaire, est une signature des structures alfvéniques qui se propagent dans le vent solaire dans la direction anti-solaire [Matteini et al., 2014]. Les switchbacks sont similaires aux ondes d'Alfvén, car leur intensité magnétique est presque constante sur toute la longueur de leur frontière. Cependant, ils ne sont pas purement alfvéniques, car ils sont également faiblement compressibles, et des décrochements de $|B|$ ont été observés à leur frontière [Farrell et al., 2020; Larosa et al., 2021]. De plus, certains pics de vitesse sont associés à une augmentation de la densité de protons, ce qui est la signature d'une composante non alfvénique [Kasper et al., 2019].

Cette propriété est cruciale pour le premier travail que je présenterai au chapitre 2. En effet, la direction du champ magnétique change lors de la traversée du switchback et, plus particulièrement, lors du passage de ses frontières. La déviation est ainsi

contrainte par l'alfvénicité, puisque l'amplitude du champ est constante. Cela oblige l'extrémité du vecteur de champ à tourner sur la surface d'une sphère. Cette propriété géométrique jouera un rôle important dans l'analyse des frontières, qui sont l'une des clés pour comprendre l'origine des switchbacks.

Si l'omniprésence des switchbacks permet des études statistiques approfondies de leurs propriétés in situ, une inconnue majeure demeure : leur origine et leurs mécanismes de formation. Plusieurs théories sont proposées, mais aucun consensus n'a encore été trouvé. Les premières théories ont été débattues après les premières orbites, lorsque [PSP](#) était encore à de grandes distances du Soleil, autour de $35 R_{\odot}$. Les switchbacks sont mesurés à des distances aussi éloignées que l'orbite de la Terre, ce qui nous permet, en théorie, de suivre leur évolution et leur propagation. Cependant, nous avons besoin de mesures plus proches de leur site d'origine pour résoudre leur formation. En effet, au cours de leur propagation, divers processus pourraient opérer au sein du vent solaire et masquer les marqueurs de leur origine.

Nous pouvons classer les théories de formation en deux catégories. La première soutient que les switchbacks sont des structures formées in situ dans le vent solaire, en fonction de conditions du plasma spécifiques. La deuxième catégorie soutient que les switchbacks sont des perturbations provenant de la basse atmosphère solaire. Ces théories sont principalement basées sur la reconnexion d'interchange, définie comme la reconnexion magnétique entre les champs fermés et ouverts [[Crooker et al., 2002](#)].

J'ai maintenant présenté le contexte global des structures d'inversion magnétique observées par [PSP](#) dans le vent solaire. Bien que les switchbacks ne soient pas nouveaux en soit, ce qui explique la grande attention qui leur a été accordée depuis que [PSP](#) est en fonctionnement, c'est leur omniprésence dans l'héliosphère interne et leur lien possible avec les mécanismes qui pourraient chauffer la couronne et le vent solaire, ainsi qu'avec l'accélération de ce dernier. Dans cette perspective, il est nécessaire d'étudier les phénomènes qui pourraient permettre à certaines structures de survivre à de grandes distances du Soleil. Si les switchbacks sont associés à des mécanismes de chauffage et d'accélération, ils doivent permettre un transfert d'énergie. Ce transfert d'énergie peut se produire à la frontière des switchbacks, qui n'est pas encore complètement caractérisée. L'origine des switchbacks est également cruciale, car elle pourrait nous éclairer sur l'origine du vent solaire. En effet, cette étude nécessiterait une analyse complète entre les mesures in situ des inversions magnétiques locales et les observations à distance des mécanismes de libération.

5.2 Résumé du chapitre 2 : La frontière des switchbacks

Les frontières des switchbacks correspondent aux intervalles de déflexions soudaines mesurés de chaque côté des structures. Elles constituent l'une des propriétés marquantes des switchbacks. Il est intéressant de noter qu'elles peuvent être étudiées dans la perspective d'une compréhension globale de l'interaction des switchbacks avec le vent solaire ambiant. La nature exacte des frontières des switchbacks est encore inconnue. Cependant, elle devrait permettre de mieux comprendre l'évolution des switchbacks

dans le vent solaire lorsqu'ils se propagent en s'éloignant du Soleil. S'agit-il de frontières ouvertes pouvant être traversées par un flux de plasma, ou de frontières fermées qui empêchent tout flux de plasma ? Leur nature pourrait également conserver une signature de l'origine de la structure et ajouter des contraintes sur les mécanismes de génération. Je m'intéresse en particulier à l'amplitude de ces déviations, en comparant des petites déviations de l'ordre de quelques dizaines de degrés à des inversions complètes du champ dans la direction opposée à la direction de la spirale de Parker, qui me sert de référence. Sans utiliser les données de vitesse du vent, une méthode empirique peut être mise en place pour déterminer la direction de la spirale en calculant une valeur médiane sur les intervalles de vents calmes où l'on n'observe pas de switchbacks. Leurs frontières sont d'un grand intérêt pour comprendre l'évolution de ces structures, et je cherche donc à en connaître les propriétés.

L'objectif de ce chapitre est de répondre aux questions ouvertes suivantes :

- Quelle est la nature des frontières des switchbacks ?
- Comment les propriétés des frontières des switchbacks sont-elles liées à leur évolution dynamique dans le vent solaire ?

Les frontières des switchbacks sont caractérisées par un changement du champ magnétique, dont la pente est presque verticale, défini comme une discontinuité du plasma. Une discontinuité est définie comme une séparation entre deux régions de plasma ayant des propriétés différentes. Dans l'approximation MHD, de telles discontinuités dans le vent solaire sont couramment décrites au moyen des relations de Rankine-Hugoniot, dont les deux principales solutions sont les Discontinuités Tangentielles (TD) et les Discontinuités Rotationnelles (RD).

Les TDs sont des structures convectées par le vent solaire. La composante du champ magnétique est tangentielle à la structure $B_n = 0$. La pression totale est conservée pour les TDs. Tout autre changement est arbitraire. Comme le champ est tangentiel, la discontinuité sépare deux plasmas qui ne sont pas magnétiquement connectés et qui peuvent donc être de composition différente. Elles ne permettent pas non plus le transport de particules à travers la discontinuité. Au contraire, les RDs se propagent avec la vitesse d'Alfvén V_A . Elles sont isentropiques et ont une composante normale du champ magnétique non nulle $B_n \neq 0$. Elles permettent le transport de particules, avec un flux de masse fini à travers la discontinuité $\rho v_n \neq 0$ et une vitesse d'écoulement normale continue $[v_n] = 0$. La principale distinction entre les deux types de discontinuités est la présence ou non d'une composante normale à la frontière. Ce paramètre est donc utilisé dans l'étude des frontières, ce qui nécessite de déterminer précisément la direction du vecteur normal à la frontière.

Dans ce chapitre, je propose de comparer deux méthodes, dont l'une est fréquemment utilisée dans de telles analyses, pour déterminer la nature de la frontière. Ceci sera directement lié aux spécificités des frontières des switchbacks par rapport aux différentes structures du vent solaire. J'utilise deux méthodes statistiques, l'Analyse de Minimum de Variance (MVA) et la Décomposition en Valeur Singulière (SVD) pour

déterminer la nature tangentielle ou rotationnelle des frontières. Cela permet également de déterminer leur longueur caractéristique.

La spécificité des frontières des switchbacks est qu'elles sont des structures avec une polarisation en arc, avec une intersection entre une sphère de rayon constant correspondant à la norme du champ magnétique et d'un plan. Ce résultat est important. Cela contraint leur analyse et explique les faiblesses de l'utilisation seule de la MVA pour déterminer leur nature. En effet, la MVA est grandement impactée par la présence d'ondes au niveau de la frontière, ce qui donne une normale relativement éloignée de la normale réelle. La nouvelle méthodologie repose sur l'application des deux méthodes pour déterminer le plan de la discontinuité en déterminant au mieux la structure en arc. L'analyse visuelle des structures en 3D ainsi que des plans calculés par les deux méthodes nous permet de déterminer la normale à la frontière. Par définition, nous pouvons ainsi déduire la nature des frontières.

La nouvelle méthodologie mise en place montre une tendance tangentielle des frontières dans plus de 70% des cas étudiés. Cela a des implications directes sur la survie des structures dans le vent solaire. L'épaisseur des frontières, principalement dans les échelles magnétohydrodynamiques, va également confirmer l'hypothèse de structures stables qui se propagent sans être érodées. L'étude de l'influence de la magnitude des déflexions montre que les structures sont auto-similaires, c'est-à-dire que les petites et grandes déflexions ont les mêmes propriétés et qu'il n'y a pas de petites structures qui seraient le résultat de l'érosion de grandes structures au cours de leur propagation. Ces conclusions sont en désaccord avec les précédentes études sur les frontières, ce qui peut s'expliquer par l'utilisation de la MVA, qui fausse les conclusions.

Ce travail conduit directement à un certain nombre de questions sur les structures et les implications avec les questions ouvertes sur le vent solaire :

- Nature de la frontière
 - Quel est l'impact de la géométrie 3D des frontières ? La structure en forme d'arc de la frontière a un impact important sur la méthodologie mise en œuvre. Cependant, on ne sait pas exactement pourquoi ce type de structure est lié aux inversions magnétiques. Cela souligne la nécessité d'effectuer des analyses 3D des frontières qui ne se limitent pas à une hypothèse plane.
 - Comment pouvons-nous établir un lien entre la nature fermée de la frontière et les propriétés alfvéniques des switchbacks ? L'alfvénicité des switchbacks est observée à leur frontière avec la rotation du vecteur de champ à la surface d'une sphère de rayon égal à l'amplitude du champ. Cependant, l'alfvénicité semble être perdue à la frontière avec la nature tangentielle de la frontière et l'absence de corrélation caractéristique dans la vitesse et le champ magnétique.
 - Y a-t-il une influence de l'amplitude de la déflexion ? Les frontières des switchbacks présentent des propriétés auto-similaires, comme les propriétés rapportées des switchbacks.

- La déflexion présente-t-elle des types distincts avec des propriétés uniques ou s’agit-il d’un spectre continu d’événements ? Les frontières présentent généralement les propriétés des discontinuités tangentielles, tandis que l’origine et l’existence des discontinuités rotationnelles restent inexpliquées. Une hypothèse pourrait être formulée quant à l’origine différente des deux types de frontières, mais elle n’empêche pas l’hypothèse d’une frontière rotationnelle qui évoluerait vers une frontière tangentielle.
- Propagation et évolution
 - Évoluent-ils au cours de leur propagation en s’éloignant du Soleil et comment ? La nature de la frontière ne montre pas d’évolution avec la distance radiale, mais il n’est pas possible de conclure sur l’évolution, car il n’y a pas de preuve, par manque de statistique, que plus on se rapproche du Soleil, plus on observe de [RD](#).
 - La frontière est-elle soumise à l’érosion et y a-t-il un transfert d’énergie ? Cette question pourrait être liée à la nature des frontières, les [TD](#) stables étant moins susceptibles d’être érodées. Un mécanisme d’érosion possible est la reconnexion magnétique à la frontière, mais l’étude de ce phénomène local est limitée pour comprendre comment la reconnexion éroderait la frontière.
 - Ces structures prennent-elles de l’ampleur au fur et à mesure qu’elles se propagent, ou leur taille est-elle prédéterminée au point d’origine ? On peut répondre à cette question spécifiquement pour les frontières, car il n’y a pas d’augmentation apparente de l’épaisseur de la frontière avec la distance radiale au Soleil, mais on observe une zone d’exclusion.
- Origine des structures
 - D’où sont-elles originaires ? Les résultats sont compatibles avec une origine ancrée dans la basse atmosphère solaire.
 - Pouvons-nous rejeter certaines théories d’origine sur la base de ces résultats ? Les résultats précédents ne nous permettent pas d’exclure la génération in situ. Cette question nécessiterait la recherche d’une source solaire pour exclure l’origine solaire, ou pour trouver une explication physique à toutes les propriétés in situ des switchbacks dans les théories de génération in situ, telles que l’auto-similarité.

Dans l’ensemble, ces résultats remettent en question l’image classique des switchbacks et suggèrent que leur érosion pourrait être beaucoup plus lente que prévu. Les switchbacks, avec leurs frontières stables, pourraient survivre plus longtemps en se propageant dans le vent solaire. Ceci encourage une étude de l’origine solaire probable des switchbacks, qui sera réalisée dans le chapitre suivant.

5.3 Résumé du chapitre 3 : L'origine des switchbacks

L'une des principales questions en suspens concernant les switchbacks est celle de leur origine. Les switchbacks sont de plus en plus étudiés in situ, ce qui permet de mieux comprendre leur nature et leur propagation. Cependant, leur origine fait toujours l'objet de débats importants, car il n'existe aucune preuve définitive de l'une ou l'autre des théories. Comme indiqué au chapitre 1, deux groupes de théories sont proposés. Le premier plaide en faveur d'une formation des switchbacks due à des événements solaires transitoires à petite échelle. Le second évoque plutôt une formation in situ dans le vent solaire, due à des phénomènes locaux. La théorie solaire est étayée par des théories et des observations. Par exemple, [Tenerani et al. \[2020\]](#) a utilisé des simulations pour discuter de l'origine des switchbacks dans la basse couronne. Cela est également mis en évidence par la longue mémoire identifiée dans le taux d'occurrence des switchbacks [[Dudok de Wit et al., 2020](#)].

Pour étudier et fournir des preuves de l'hypothèse d'une origine solaire, nous devons maintenant explorer les processus nécessaires qui conduiraient à des inversions magnétiques mesurées in situ. L'étape initiale se situe dans la basse atmosphère solaire. Il faut commencer par une ligne de champ, ancrée dans la basse atmosphère solaire. Un processus initial est alors nécessaire pour créer une perturbation du champ magnétique. Cette perturbation se propage ensuite le long de la ligne de champ dans l'atmosphère vers l'espace interplanétaire, afin que le satellite puisse la rencontrer. Dans cette description, certains problèmes peuvent être directement détectés. Les processus qui perturbent les lignes de champ pour créer une perturbation doivent contrecarrer la tension magnétique de la ligne pour que la perturbation puisse survivre. Certains processus proposés dans la littérature ont donc peu de chances de perdurer. L'un d'entre eux est la génération d'un renversement d'une seule ligne de champ directement dans la couronne [[Fisk and Kasper, 2020](#)]. Avec la nécessité d'avoir une structure qui survit, la condition suivante est la capacité à s'échapper de la couronne. La structure doit se propager sur de grandes distances. Cela est possible dans le cas de lignes de champ ouvertes, qui permettraient à la perturbation d'échapper à la couronne, alors que des lignes de champ fermées l'en empêcheraient.

Parmi les processus qui pourraient être impliqués ici, il y a un consensus croissant sur le rôle clé que jouent les événements énergétiques à petite échelle causés par la reconnexion magnétique dans la création des conditions favorables pour la génération de switchbacks. En effet, de nombreuses études solaires montrent que des événements transitoires omniprésents sont capables d'éjecter de la masse et des ondes dans l'espace interplanétaire [[Raouafi et al., 2016](#)]. [Wang et al. \[1998\]](#) ont montré que le plasma est éjecté à une vitesse d'environ 250 km s^{-1} pour les jets polaires identifiés dans les bandes EUV. [Paraschiv et al. \[2012\]](#) a estimé la masse moyenne éjectée qui pourrait contribuer au flux lent du vent solaire. Dans [Lee et al. \[2014\]](#), des jets ont été simulés dans une région de flux émergent et la propagation d'ondes d'Alfvén a été mise en évidence dans la couronne à la suite d'un mouvement de détorsion de la structure. Ces simulations sont étayées par des observations de flux atteignant la vitesse d'Alfvén

locale dans le jet [e.g., [Cirtain et al., 2007](#)]. Les ondes pourraient évoluer pour aboutir aux structures magnétiques observées par PSP. Cependant, cela n'a pas encore été prouvé. La présente analyse a pour but d'apporter des contraintes sur les mécanismes de génération en vue de trouver les précurseurs solaires des switchbacks, en se concentrant sur les théories des événements transitoires à petite échelle.

La plupart des études visant à prouver l'origine solaire des switchbacks se sont concentrées soit sur leurs propriétés in situ, soit sur la télédétection de leurs sources solaires possibles. Le fait de se concentrer exclusivement sur les mesures de l'inversion ou sur les phénomènes solaires limite la recherche de preuves concluantes, car cela introduit un biais évident dans l'interprétation des données. La comparaison directe entre les phénomènes éruptifs récurrents et les switchbacks est difficile. L'absence de conclusions sur l'origine des switchbacks est principalement liée à la difficulté de relier les événements transitoires mesurés in situ aux événements transitoires qui se produisent dans la basse couronne.

Les difficultés viennent du fait qu'il existe des complexités inhérentes à ce type d'étude qui compare l'entrée et la sortie d'un système complexe impliquant plusieurs mécanismes physiques, chacun ajoutant une nouvelle couche d'incertitudes.

Les petits événements transitoires qui peuvent être observés dans les images EUV au-dessus du limbe se mélangent rapidement avec les intensités de fond à de faibles distances dans la couronne. Le contraste de densité plus faible se traduit par une faible intensité dans les images. Actuellement, il n'existe aucun instrument qui nous permettrait de suivre un événement éruptif à petite échelle jusqu'aux distances de PSP. Les limitations sont dues aux faibles cadences et résolutions spatiales des instruments couvrant une grande distance du Soleil, ainsi que le faible contraste en densité. Le coronographe LASCO-C2, par exemple, fournit une image de la couronne entre 1,5 et 6 rayons solaires toutes les 20 minutes, avec une résolution spatiale de 23'' par pixel. Les échelles impliquées dans les événements éruptifs sont relativement plus petites et ne seraient pas détectées dans les images du coronographe C2.

Nous devons alors nous appuyer sur des modèles du champ magnétique pour déterminer la connectivité du satellite avec la surface solaire. Cette approche de modélisation est une source d'incertitudes qui pourrait avoir un impact sur les conclusions des précurseurs de l'inversion. Certaines incertitudes peuvent être levées et incluses dans le processus, ce qui est une exigence claire pour explorer l'hypothèse d'une source d'inversion dans la basse couronne.

Les switchbacks sont omniprésents dans le vent solaire, et les événements qui produisent les conditions de leur génération devraient donc être aussi nombreux, voire plus. Ils devraient également être générés tout au long du cycle solaire en l'absence de régions actives et de larges trous coronaux. L'omniprésence spatiale et temporelle des éruptions à petite échelle, c'est-à-dire des jets [e.g. [Shibata et al., 1992](#); [Raouafi et al., 2016](#)], la plupart provenant d'amas de boucles à petite échelle connues sous le nom de CBP [[Madjarska, 2019](#)], en font les candidats les plus évidents pour créer des switchbacks. Certaines études ont estimé le taux d'occurrence des CBP à 570 CBP par jour sur le disque [[Alipour and Safari, 2015](#)]. On trouve des CBP dans toutes les

régions de l’atmosphère solaire, y compris dans le [QS](#), les [CH](#) et près de [AR](#). C’est l’une des raisons pour lesquelles les [CBP](#) sont étudiés dans la recherche de précurseurs des switchbacks. Je me concentre donc sur les [CBP](#) et les événements éruptifs produits à leur emplacement. Cette partie du travail a été réalisée en collaboration avec Maria S. Madjarska, grâce à son expertise sur les [CBP](#) et les éruptions à petite échelle.

Afin de déduire l’emplacement de la source sur la surface solaire d’une mesure in situ du vent solaire, l’une des méthodes les plus courantes est basée sur un processus appelé « back mapping » du vent solaire [e.g., [Badman et al., 2020](#); [Koukras et al., 2022](#)]. L’étude de la connectivité est basée sur une méthodologie standard en deux étapes. La première étape est une modélisation balistique suivant une spirale de Parker, avec comme paramètre la vitesse du vent solaire. La deuxième étape est une modélisation magnétique, basée sur l’extrapolation du champ photosphérique. L’analyse de la connectivité sera effectuée sur des intervalles dans les séries temporelles de [PSP](#) pour lesquelles je peux récupérer des images co-temporelles de la surface solaire.

L’analyse initiale de toutes les périodes de corotation disponibles a révélé un résultat inattendu majeur : une multiple connectivité avec les zones de source solaire en fonction de la hauteur de la surface de la source. Dans la plupart des cas, plusieurs régions de flux magnétique ouvert, telles que définies par le modèle [PFSS](#), ont pu être connectées au satellite. En outre, la méthodologie de connectivité standard a montré des limites significatives, qui ont impacté notre analyse des événements transitoires à petite échelle liés à l’ouverture locale du champ.

Je n’ai donc pris en compte que les quelques cas pour lesquels une connectivité sans ambiguïté a pu être établie. J’ai observé un niveau d’activité similaire (jets et switchbacks) en fonction de la taille du trou coronal connecté à [PSP](#). Toutefois, je n’ai pas trouvé de corrélation temporelle claire entre le nombre de jets provenant de la région source et le nombre de switchbacks à [PSP](#). La sélection des événements peut avoir un impact notable sur les résultats, en fonction de la sous-région considérée et de la capacité instrumentale à détecter certains jets. Enfin, les résultats peuvent être influencés par notre compréhension limitée des processus évolutifs qui se produisent pendant la propagation du vent solaire.

Les travaux futurs devraient se concentrer sur l’affinement de l’identification des jets afin d’éviter les limitations de l’échantillonnage. Les problèmes de connectivité pourraient être résolus en utilisant des modèles d’extrapolation plus complexes et combinés, tenant compte des petites échelles et de la nature transitoire des événements.

5.4 Résumé du chapitre 4 : Conclusions générales et perspectives

Le chapitre 1 traite de l’héliosphère, en mettant l’accent sur le Soleil en tant que source d’énergie. Malgré des recherches approfondies, des mystères subsistent, comme la couronne exceptionnellement chaude par rapport à la surface solaire et l’origine du vent solaire. Le chapitre met en lumière la découverte de « switchbacks », des

déviation magnétique par rapport à la spirale de Parker, identifiés par une récente mission solaire [PSP](#). Ces déflexions ont deux origines hypothétiques principales : la génération in situ dans le vent solaire dans des conditions de plasma spécifiques, ou des perturbations de la basse couronne dues à la reconnexion par interchange. Ce travail a pour but d'étudier l'origine et la dynamique de ces déflexions dans le vent solaire.

Le chapitre 2 examine les frontières des switchbacks afin de déterminer leur capacité à échanger de la masse et de l'énergie avec le vent solaire. Les frontières peuvent être considérées comme des discontinuités [MHD](#) habituelles, avec les discontinuités tangentielles et rotationnelles. La première orbite de [PSP](#) autour du Soleil a montré des frontières avec des signatures proches des discontinuités tangentielles idéales, ce qui suggère qu'il s'agit de structures fermées qui inhibent l'écoulement du plasma. Cela leur permet potentiellement de persister sur de longues distances. Cette caractéristique s'applique à tous les angles de déflexion, ce qui correspond à la nature autosimilaire des switchbacks. Les résultats sont compatibles avec une origine solaire de ces structures, bien qu'une formation in situ ne puisse être exclue.

Après les résultats du chapitre 2, le chapitre 3 présente l'étude de l'origine solaire possible des switchbacks. J'explore l'hypothèse d'une source des switchbacks dans la couronne inférieure en combinant des observations in situ et des observations par télédétection, en utilisant une méthodologie rigoureuse pour relier les deux mesures. En me concentrant sur deux intervalles pendant lesquels [PSP](#) était en corotation avec le Soleil, je trouve un niveau d'activité correspondant entre les jets et les switchbacks, en fonction de la taille de la région connectée à [PSP](#). Je détecte également visuellement des tendances similaires dans le nombre de jets provenant de la région source estimée et le nombre de switchbacks mesurés par [PSP](#). Cependant, aucune corrélation n'est observée entre les séries temporelles des nombres d'événements. Si cette absence de corrélation peut être liée à des incertitudes dans la connectivité et l'identification des jets, elle peut aussi indiquer qu'il n'y a pas de relation entre les jets et les switchbacks.

Dans l'ensemble, cette thèse apporte une nouvelle compréhension de la capacité des switchbacks à évoluer dans le vent solaire, mais montre les nouveaux défis à relever pour relier les switchbacks au chauffage et à l'accélération du vent solaire. Elle montre également que les modèles simples ne sont pas encore suffisants pour valider la théorie d'une origine solaire des switchbacks, mais met en évidence la voie pour de futures études afin de résoudre les sources d'incertitudes restantes, y compris la connaissance limitée de la propagation des événements transitoires qui pourraient être résolus par des simulations numériques, ainsi qu'une meilleure compréhension physique.

Appendices

Investigation on the EUV SWAP data to track eruptive events

As part of the Guest Investigator Program organized by the PROject for OnBoard Autonomy 2 (PROBA-2) team at the Royal Observatory of Belgium, I collaborated with the PI team of the SWAP (Sun Watcher using Active Pixel System detector and Image Processing) telescope on ESA's PROBA-2 mission to determine whether the unique wide field of that instrument could benefit our studies. The PI team also have knowledge of the processing of the data, with the best parameters to obtain the faint coronal magnetic structures out of the EUV images.

I used images from a second instrument, SWAP on board PROBA-2. SWAP is an EUV telescope designed to provide images of the solar corona. The passband is centered at $174\text{ \AA}$, and it images the corona at a cadence of about 2 min [Seaton et al., 2013]. The instrument has a larger FOV, spanning $54'$, than AIA, which covers $41'$, as shown in Figure A.1. That is interesting in this study, as I aim to track plasma erupting from the Sun out to larger distances. The spacecraft can also point off the disk center to capture plasma at even larger distances, $2\text{--}3 R_{\odot}$. That may allow for the following structures to erupt from the Sun for a longer time. It could give some insight into the possible connection of the eruptive events with PSP. The large FOV is indeed an advantage that can allow tracking the densest part of those eruptive events that escape the corona. The idea would not be to trace the structure back to PSP but to understand the dynamics of magnetic structures in the corona. As highlighted in Chapter 3, the ability of eruptive events to escape the corona is largely open question. However, the interest of SWAP resides in the investigation of sources that would be located at the limb. Here, the larger FOV would be directly interesting to follow the density enhancement to larger distances, which would indicate their ability to escape the corona.

It should be noted that the spatial resolution of SWAP is lower than AIA: a pixel of SWAP corresponds to $3.16''$, compared to $0.6''$. Moreover, the more pronounced degradation of the instrument may prevent the analysis of the faint events that I want to investigate. The PROBA-2 spacecraft was launched in 2009.

I analyzed different eruptive events that we observed in AIA 193 images and had the capacity to leave the corona. They served as test cases to show the possible use of SWAP in this investigation. I applied different commonly used filters to enhance the coronal structures off-limb. These included Wavelets Enhanced Whitening (WOW) [Auchère et al., 2023], Noise Adaptative Fuzzy Equalization (NAFE) [Druckmüller,

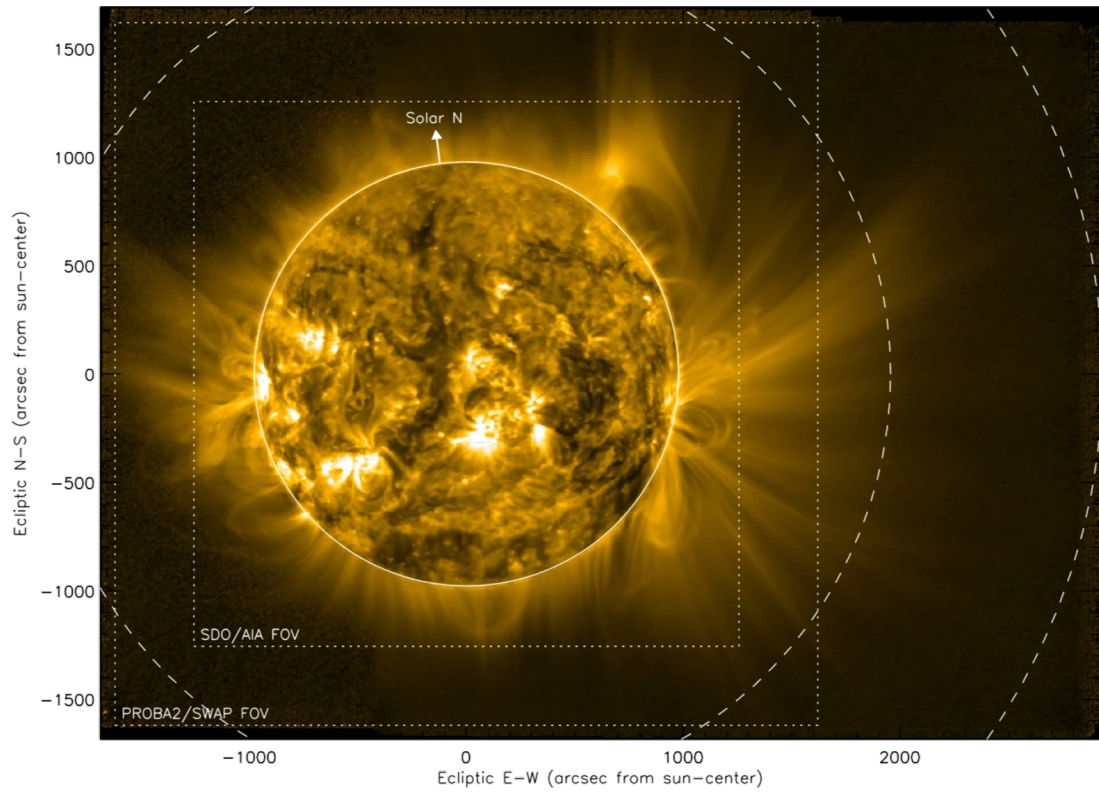


Figure A.1: SWAP extended FOV compared to AIA. Reproduced from [West et al. \[2022\]](#).

2013], Multi-Scale Gaussian Normalization (MGN) [Morgan and Druckmüller, 2014], and a filter implemented in Sunpy [Community et al., 2020], which is based on a fit of the intensity as a function of the radial distance to the Sun center. Over the limb, the intensity decreases, but the linear fit in the linear-log space locally increases the off-disk intensity.

The **WOW** filter implements filtering at all scales and locations using à-trous wavelet transform. The power of the wavelet spectrum of the image is equalized. Then, it results in output images with sharp contrast between structures. The filter is optimized because it does not require one to set any parameter. The filter is also faster than the more widely used MGN filter. The **WOW** filter can be used by nontrained users without the need to adjust the filter for each image. For these reasons, I will mostly discuss the **WOW** filter and compare it to the local filter implemented by the **SWAP** PI team. The underlying principle of the **WOW** method is the equalization, or whitening, of power in the à-trous wavelet spectrum of the input image at all scales and locations.

However, the conclusion from the tests is that only large and dense eruptive events may be tracked to distances larger than the **FOV** of **AIA**. However, these eruptive events are not the jets from **CBPs** I am considering. In that case, their size is relatively small, and the density over the limb is small, so the intensity of the jet is highly difficult to distinguish in the images. The **SWAP** images include a certain level of noise on the off-limb part of the image. The different filters did not improve the identification. Figure A.2 shows an example of the **SWAP** image processes with the **WOW** filter to enhance off-limb structures. Large structures are visible but are rapidly undistinguished at larger distances. I present in Figure A.3 a comparison of the same **FOV** at similar times taken by **AIA** and **SWAP**. Both images are processed using **WOW** technique. It clearly shows that, while **SWAP FOV** is larger, the structures are observed until the same heights. The structures are better resolved with **AIA** than **SWAP**.

To conclude on the use of **SWAP** images to improve the investigation of the jets' propagation, the opportunity of the larger **FOV** would not be an advantage due to the low resolution of the instrument and the impossibility to retrieve the jet signals from the background noise.

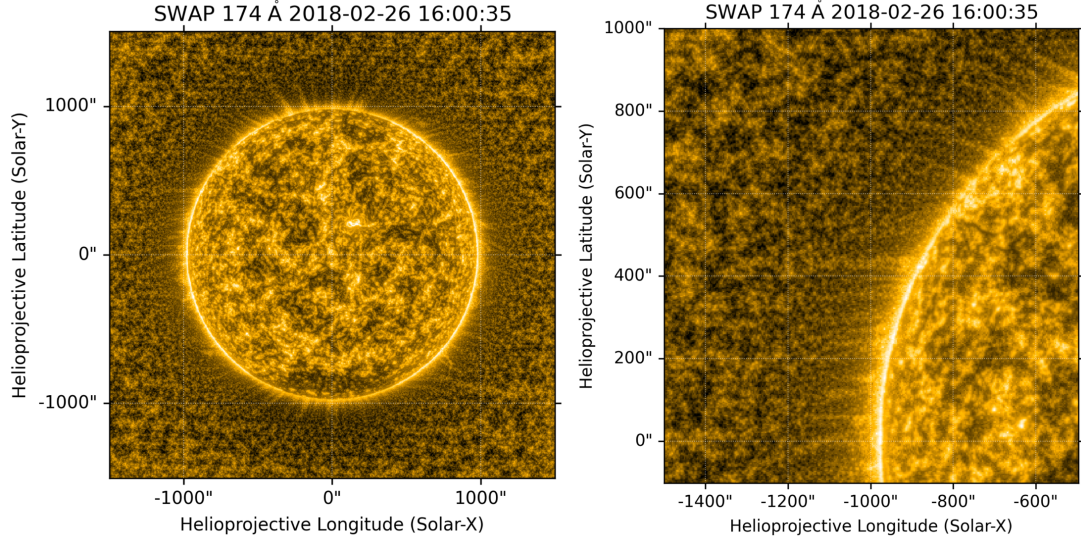


Figure A.2: Implementation of the **WOW** filter on **SWAP** EUV images. Full disk view and submap on a region with eruptive events. The background noise hides the signal of the jet at relatively close distance to the Sun.

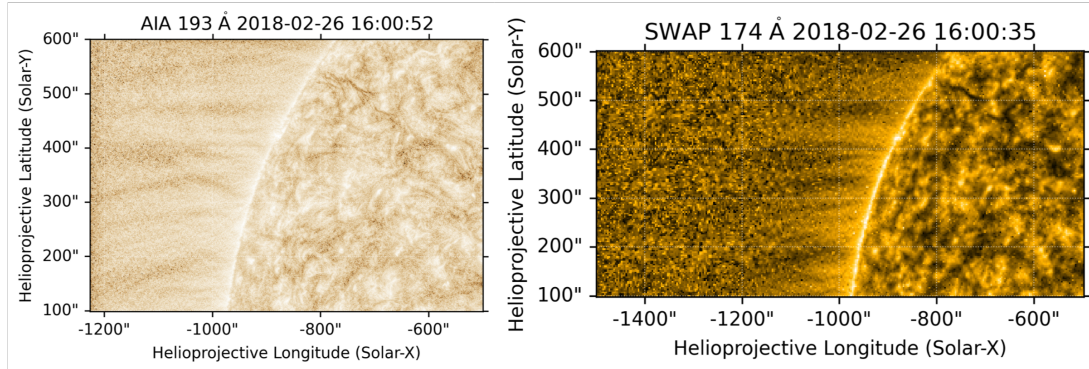


Figure A.3: Comparison of **AIA** and **SWAP** images taken at the same time. Both images are processed with the **WOW** filter. **AIA** resolution is larger, which allows following the jets to larger distances than **SWAP** despite the larger **FOV** of **SWAP**.

Techniques to be implemented to enable automation

B.1 Region growing attempt to refine an automatic detection

While the automatic detection of brightenings in EUV images is fast and convenient to process automatically the cube, as presented in Section 3.4.3, it does not allow for a full automatic analysis to count the number of jets. However, it is really complex to move from the pixel identification to an event identification. Indeed, there is no easy size or duration threshold for an identification to be a real eruptive event. From each pixel identified, we could then use a region-growing algorithm¹ to group neighboring identified pixels into single event. To do so, I perform a Gaussian blur on the brightening pixel image. Then, for each pixel detected inside a 2D shape, the region growing code is used to obtain a 3D voxel, that correspond to the spatial and temporal identification of the jet. That is performed until all pixels of the cube belong to a voxel. I retrieve the largest area 2D cut in time to overlap it with the EUV images for context.

What is interesting about this technique is that it allows for a comprehensive estimation of the influence of the area of the region considered for the counting of events. Indeed, manual visual identification could be biased by the operator-set boundary limits of the region to investigate. That has more impact when the CH connected to the spacecraft is large, and the footprint given by the connectivity procedure covers a relatively large area. In that case, the source region considered for the counts of jets should include all the uncertainties. That may be over (or under) estimating the area. One would need to refine the area between different counting of the jet and study the influence of the size of the included area. However, what becomes more complex is the identification of real events compared to the trained operator visual identification. I started with the determination of the minimal size of one eruptive event that would not be considered noise. In the literature, the smallest eruptive events detected on AIA 193 are jetlets [Raouafi et al., 2023]. However, these are only observed at the base of plumes, which is not the case for the events I investigate. The size of one pixel in AIA is $430 \times 430 \text{ km}^2$ or $0.6''/\text{pixel}$.

In our region-growing procedure, I would have to define a lower limit to consider the pixels to form one single jet event. However, this would only be the first step in

¹[skimage.morphology.flood](#)

identifying the events. The limit is however, unclear, due to the possibility to include events that are just brightenings and not jet. This explains why this type of analysis was not performed in the main analysis presented in Chapter 3.

I tried to implement the region growing technique with a 5 pixels limit, that would correspond to a minimal size of $3''$ but I realized that while the technique identifies efficiently some jets, it appears to miss the largest eruptions, which are clearly visible in the videos. Then, it would mean a double check of all videos to make sure no large eruptions were missed. This is clearly not the goal of this attempted procedure.

After a trade-off between the possible gain of time to constraint such methodology, with the necessity to combine it with ground-based observations not always available, that would remove false detection compared to manual and visual identification of individual eruptions, I decide to keep the manual process. Indeed, it is time-consuming and has a risk of not reaching an improved and rigorous identification procedure.

B.1.1 Detection of recurrent jetting from the same CBP

When counting individual jets, I directly observe that some events are more complex showing recurring jets from the same CBP, which could be mistaken for a single jet. This has been observed before by [Madjarska \[2011\]](#) and [Chen et al. \[2015\]](#). Visually, it can become complex to count single events. That adds some complexity to the link with the switchbacks as discussed in Section 3.6.

The idea here would be to resolve the number of jets per CBP. I tried to implement a method that would allow for counting jets with successive eruptive events. One possibility was to select an area in the EUV image that would include the CBP. Then, I can compute the mean of the intensity in that area per frame. Ideally, peaks should be observed when a jet occurs. In the case of recurring jets, the peaks could be distinguished from each other.

I present in Figure B.1 an example with an event that occurred during the E15. The area included in the mean computation is highlighted by the black rectangle. I show the mean intensity computed over this region over the time dimension of the data cube in Figure B.2. No clear peak is striking above the background, and I visually find more than two jets. The method could be implemented for future studies, but this shows directly the level of difficulty that one would face when investigating such procedure. It may be necessary to define clearly the background to allow for a higher variability in the intensity. It could be combined with the brightening identification code I presented above, which is mainly based on a local background estimation. As the code is developed per pixel, some changes would then be necessary. It is not applied in the analysis presented in Chapter 3, as the visual identification is better performed and more time efficient.

B.1.2 Perspectives on the techniques

Both techniques presented here could be potential solutions to resolve some of the uncertainties in the jet's identification and allow us for automatic detection. However,

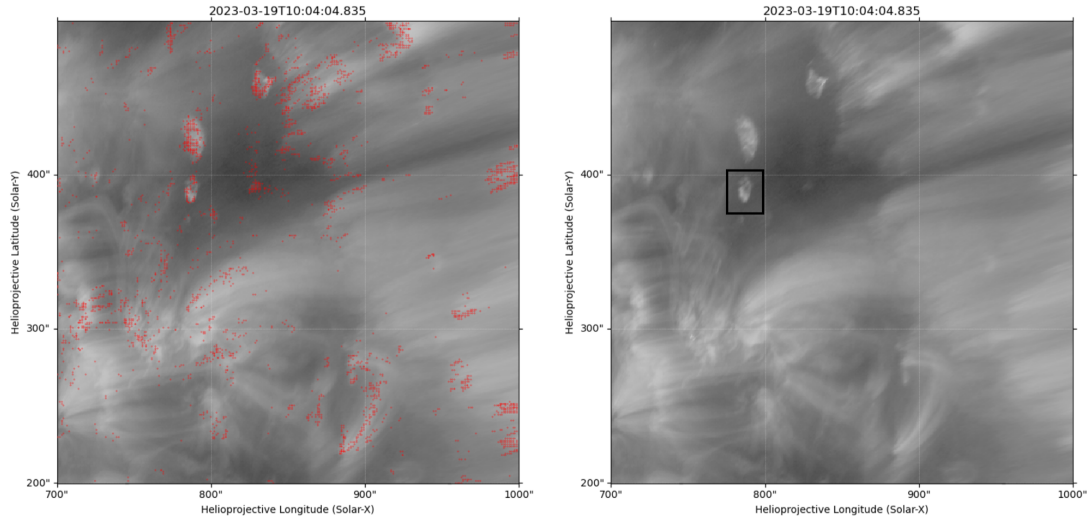


Figure B.1: Example of an event with recurring jets. The black rectangle corresponds to the area considered for the intensity analysis.

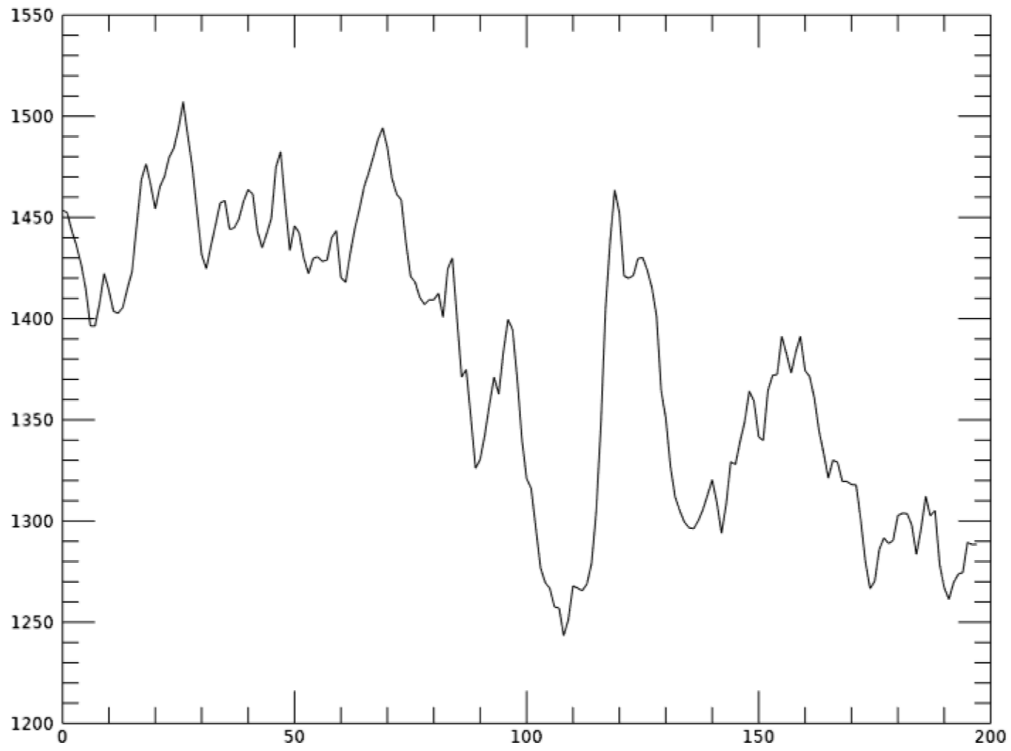


Figure B.2: Mean intensity over the region presented in Figure B.1. The x-axis is the frame number in the data cube. The y-axis represents an intensity value. The peak at the 120 frame is a jet, but the previous jet is not distinguished above the background.

it is still clear that this is not easy to implement and would require further investigation.

List of publications and communications

C.1 Publications

Bizien, N., Dudok De Wit, T., Froment, C., Velli, M., Case, A. W., Bale, S. D., Kasper, J., Whittlesey, P., MacDowall, R., and Larson, D. (2023). Are Switchback Boundaries Observed by Parker Solar Probe Closed? *The Astrophysical Journal*, 958(1):23

Bizien, N., Froment, C., Madjarska, M. S., Dudok De Wit, T., Velli, M., (2025) Tracing magnetic switchbacks to their source: a critical assessment of solar coronal jets as switchback precursors, *Astronomy & Astrophysics*, 694, A181

Samuel T. Badman, Naïs Fargette, Lorenzo Matteini, Oleksiy V. Agapitov, Mojtaba Akhavan-Tafti, Stuart D. Bale, Srijan Bharati Das, **Nina Bizien**, Trevor A. Bowen, Thierry Dudok de Wit, Clara Froment, Timothy Horbury, Jia Huang, Vamsee Krishna Jagarlamudi, Andrea Larosa, Olga Panasenco, Nour E. Raouafi, Alexis P. Rouillard, David Ruffolo, Nikos Sioulas, Shirsh Soni, Luca Sorriso-Valvo, Gabriel Ho Hin Suen, Marco Velli, Jaye Verniero, Properties of Magnetic Switchbacks Measured in the Near-Sun Solar Wind, *Space Science Reviews* in preparation, ISSI Magnetic Switchbacks in the Young Solar Wind

Alfred Mallet, Chen Shi, Anna Tenerani, Oleksiy Agapitov, Mojtaba Akhavan-Tafti, Samuel Badman, **Nina Bizien**, Trevor Bowen, Mihir Desai, James F. Drake, Andrea Larosa, Francesco Malara, Lorenzo Matteini, Mathew Owens, Victor Réville, Nikos Sioulas, Shirsh Soni, Luca Sorriso-Valvo, Jonathan Squire¹ Gabriel Suen, Marc Swisdak, Marco Velli, Jaye Verniero, Nicholas Watkins, Timothy Horbury, Evolution and impact of switchbacks throughout the heliosphere, *Space Science Reviews* in preparation, ISSI Magnetic Switchbacks in the Young Solar Wind

C.2 Orals

COSPAR (Athens, 2022): Statistical investigation of switchbacks boundaries properties observed by Parker Solar Probe

FIELDS team meeting (Berkeley, 2022): Statistical investigation of switchbacks properties observed by Parker Solar Probe

Solar Orbiter Kinetic Physics Working Group (online, 27-10-2022): Switchbacks Boundaries Observed by Parker Solar Probe: An Analysis to Reveal their Dynamical Evolution in the Solar Wind

4th Parker Solar Probe Scholars (online, 8/9-11-2022): Switchbacks Boundaries Observed by Parker Solar Probe: An Analysis to Reveal their Dynamical Evolution in the Solar Wind

Journées Jeunes Chercheurs (J2C) (Orléans, 20/21-03-2023): Characterization of discontinuities in the solar wind with Parker Solar Probe

PSP switchback working group (online, 11-04-2023): Are Switchbacks Boundaries Observed by Parker Solar Probe all Closed?

Seminar at LPC2E (Orléans, 20-04-2023): What are magnetic Switchbacks observed in the Solar Wind and what is their solar origin ?

Seminar at ROB (Brussels, 16-06-2023): What are magnetic switchbacks observed in the solar wind and what is their solar origin ?

Workshop on switchbacks at ISSI (Bern, 18/22-09-2023): Are switchback boundaries observed by Parker Solar Probe closed?

FIELDS team meeting (Berkeley, 08/09-12-2023): Connecting in situ measurements and solar EUV images to investigate the sources of magnetic switchbacks

PNST (Marseille, 08/12-01-2024): Connecting in situ measurements and solar EUV images to investigate the sources of magnetic switchbacks

RPW/FIELDS workshop (Orléans, 26/29-02-2024): Properties of Switchback boundaries in the solar wind

7th Parker Heliophysics Scholars (online, 28-05-2024): Detecting potential sources of magnetic switchbacks in the lower corona by combining in situ and remote sensing observations

C.3 Posters

Solar Orbiter Summer School (Sète, 2022): Investigation of switchback properties observed by Parker Solar Probe

AGU Fall Meeting (Chicago, 2022): Switchbacks Boundaries Observed by Parker Solar Probe: Statistical Analysis to Reveal their Dynamical Evolution in the Solar Wind

Journées CNES Jeunes Chercheurs (JC2) (Toulouse, 11/13-10-2023): Are Switchback boundaries observed by Parker Solar Probe closed?

AGU Fall Meeting (San Francisco, 2023): Connecting in situ measurements and solar EUV images to investigate the sources of magnetic switchbacks

PNST (Marseille, 08/12-01-2024): Are Switchbacks boundaries observed by Parker Solar Probe closed?

ESPM 17th (Turin, 2024): Tracing magnetic switchbacks to their source: Are coronal jets the main switchback precursors?

Outreach Actions and Commitments

Representative of PhD students and postdoctoral of the laboratory, LPC2E, 2022/2023

Déclic 2021 et 2022, Lycée Jean Zay, Orléans: Participation à des tables rondes avec lycéen.nes sur l'expérience de doctorat et de femme dans le monde de la recherche

Edifice Laboratoire, 2021/2022: Supervision of 6 students in Terminale, to work on their project for the high school baccalaureate oral exam in Physics

Edifice Controverses, Lycée Pothier, Orléans, 2021/2022: Collaboration for a semestre with two high school classes (non-scientific specialization) on controversial scientific research

Supervision internship of level Master 1, LPC2E, 2022/2023: Project: Study of the interval selection on the nature of the switchback boundaries - Ghadir Ollaic

Co-Supervision internship of level Master 1, LPC2E, 2023/2024: Project: Study of the radial evolution of the nature of switchback boundaries - Tristan Vergé

Project Year of Physics, Lycée Emile Zola, Châteaudun, 15-02-2024: Discussion with high school students on space sciences in general and opportunities for their future career

Middle school interns, LPC2E, 23-02-2024: Supervision of middle school students to discuss my PhD subject and solar/plasma physics field

Member of the Local Organization Committee for the workshop RPW/-FIELDS, Orléans, 01-2024 – 02-2024: Chair of a session, organization of sessions and logistics

List of Acronyms

EUV Extreme Ultra Violet	9
HCS Heliospheric Current Sheet	21
NASA National Aeronautics and Space Administration	16
ESA European Space Agency	143
STEREO Solar TERrestrial RELations Observatory	40
Solo Solar Orbiter	79
SDO Solar Dynamics Observatory	10
AIA Atmospheric Imaging Assembly	10
PSP Parker Solar Probe	15
SPC Solar Probe Cup	38
SCM Search Coil Magnetometer	17
SWEAP Solar Wind Electrons Alphas and Protons	16
SPAN-E Solar Probe ANalyzers—Electrons	43
SPAN-I Solar Probe ANalyzers—Ions	43
PROBA-2 PRoject for OnBoard Autonomy 2	88
SOHO Solar and Heliospheric Observatory	91
SWAP Sun Watcher using Active Pixel System detector and Image Processing	88
GONG Global Oscillations Network Group	107
ADAPT Air Force Data Assimilative Photospheric Flux Transport	108
HMI Helioseismic and Magnetic Imager	107
LASCO Large Angle and Spectrometric Coronagraph	87
MMS Magnetospheric Multiscale	77
JSOC Joint Science Operations Center	96
MVA Minimum Variance Analysis	49
SVD Singular Value Decomposition	52

PFSS Potential Field Source Surface	101
NLFFF Non-Linear Force-Free Field	141
MHD Magnetohydrodynamics	16
WOW Wavelets Enhanced Whitening	167
CD Contact Discontinuity	36
TD Tangential Discontinuity	36
RD Rotational Discontinuity	36
ED Either Discontinuity	65
ND Neither Discontinuity	67
FOV Field Of View	43
AR active region	9
CH coronal hole	9
QS quiet Sun	9
CBP coronal bright point	89
XBP X-ray bright point	91
CME Coronal Mass Ejection	11
SECCHI Sun Earth Connection Coronal and Heliospheric Investigation	145

Bibliography

- Abbo, L., Ofman, L., Antiochos, S., Hansteen, V., Harra, L., Ko, Y.-K., Lapenta, G., Li, B., Riley, P., Strachan, L., von Steiger, R., and Wang, Y.-M. (2016). *Slow Solar Wind: Observations and Modeling*. (Cited on page 9.)
- Acuña, M. H. (2002). Space-based magnetometers. *Review of Scientific Instruments*, 73(11):3717–3736. (Cited on page 40.)
- Agapitov, O. V., Drake, J. F., Swisdak, M., Bale, S. D., Horbury, T. S., Kasper, J. C., MacDowall, R. J., Mozer, F. S., Phan, T. D., Pulupa, M., Raouafi, N. E., and Velli, M. (2022). Flux Rope Merging and the Structure of Switchbacks in the Solar Wind. *The Astrophysical Journal*, 925(2):213. (Cited on pages 78 and 140.)
- Agapitov, O. V., Wit, T. D. d., Mozer, F. S., Bonnell, J. W., Drake, J. F., Malaspina, D., Krasnoselskikh, V., Bale, S., Whittlesey, P. L., Case, A. W., Chaston, C., Froment, C., Goetz, K., Goodrich, K. A., Harvey, P. R., Kasper, J. C., Korreck, K. E., Larson, D. E., Livi, R., MacDowall, R. J., Pulupa, M., Revillet, C., Stevens, M., and Wygant, J. R. (2020). Sunward-propagating Whistler Waves Collocated with Localized Magnetic Field Holes in the Solar Wind: *Parker Solar Probe* Observations at 35.7 $R_{\odot}$ Radii. *The Astrophysical Journal*, 891(1):L20. (Cited on page 80.)
- Akhavan-Tafti, M., Kasper, J., Huang, J., and Bale, S. (2021). Discontinuity analysis of the leading switchback transition regions. *Astronomy & Astrophysics*, 650:A4. (Cited on pages 67, 68, 69 and 150.)
- Akhavan-Tafti, M., Kasper, J., Kasper, J. C., Huang, J., and L. Thomas (2022). Magnetic Switchbacks Heat the Solar Corona. *The astrophysical journal*, 937(2):L39–L39. (Cited on pages 67 and 70.)
- Alipour, N. and Safari, H. (2015). Statistical properties of solar coronal bright points. *The Astrophysical Journal*, 807(2):175. (Cited on pages 89, 96 and 162.)
- Altschuler, M. D. and Newkirk, G. (1969). Magnetic Fields and the Structure of the Solar Corona. I: Methods of Calculating Coronal Fields. *Solar Physics*, 9:131–149. (Cited on pages 104 and 109.)
- Antolin, P., Pagano, P., Testa, P., Petralia, A., and Reale, F. (2021). Reconnection nanojets in the solar corona. *Nature Astronomy*, 5:1–9. (Cited on page 89.)
- Arge, C. N., Henney, C. J., Koller, J., Compeau, C. R., Young, S., MacKenzie, D., Fay, A., Harvey, J. W., Maksimovic, M., Issautier, K., Meyer-Vernet, N., Moncuquet, M., and Pantellini, F. (2010). Air Force Data Assimilative Photospheric Flux Transport (ADAPT) Model. pages 343–346, Saint-Malo, (France). (Cited on page 108.)

- Arregui, I. and Van Doorselaere, T. (2024). Coronal heating. (Cited on page 5.)
- Aschwanden, M. J. (2005). *Physics of the Solar Corona*. Springer Praxis Books. Springer Berlin Heidelberg. (Cited on page 6.)
- Auchère, F., Soubrié, E., Pelouze, G., and Buchlin, (2023). Image enhancement with wavelet-optimized whitening. *Astronomy & Astrophysics*, 670:A66. (Cited on page 167.)
- Babcock, H. W. (1967). The Zeeman effect in astrophysics. *Physica*, 33(1):102–121. (Cited on page 107.)
- Badman, S. T., Bale, S. D., Martínez Oliveros, J. C., Panasenco, O., Velli, M., Stansby, D., Buitrago-Casas, J. C., Réville, V., Bonnell, J. W., Case, A. W., Dudok de Wit, T., Goetz, K., Harvey, P. R., Kasper, J. C., Korreck, K. E., Larson, D. E., Livi, R., MacDowall, R. J., Malaspina, D. M., Pulupa, M., Stevens, M. L., and Whittlesey, P. L. (2020). Magnetic Connectivity of the Ecliptic Plane within 0.5 au: Potential Field Source Surface Modeling of the First Parker Solar Probe Encounter. *The Astrophysical Journal Supplement Series*, 246(2):23. (Cited on pages 97, 109, 111 and 163.)
- Badman, S. T., Riley, P., Jones, S. I., Kim, T. K., Allen, R. C., Arge, C. N., Bale, S. D., Henney, C. J., Kasper, J. C., Mostafavi, P., Pogorelov, N. V., Raouafi, N. E., Stevens, M. L., and Verniero, J. L. (2023). Prediction and Verification of Parker Solar Probe Solar Wind Sources at 13.3 R. *Journal of Geophysical Research: Space Physics*, 128(4):e2023JA031359. (Cited on pages 103, 125 and 142.)
- Baker, D., Démoulin, P., Yardley, S. L., Mihailescu, T., Van Driel-Gesztelyi, L., D’Amicis, R., Long, D. M., To, A. S. H., Owen, C. J., Horbury, T. S., Brooks, D. H., Perrone, D., French, R. J., James, A. W., Janvier, M., Matthews, S., Stangalini, M., Valori, G., Smith, P., Cuadrado, R. A., Peter, H., Schuehle, U., Harra, L., Barczynski, K., Berghmans, D., Zhukov, A. N., Rodriguez, L., and Verbeeck, C. (2023). Observational Evidence of S-web Source of the Slow Solar Wind. *The Astrophysical Journal*, 950(1):65. (Cited on page 143.)
- Bale, S. D., Badman, S. T., Bonnell, J. W., Bowen, T. A., Burgess, D., Case, A. W., Cattell, C. A., Chandran, B. D. G., Chaston, C. C., Chen, C. H. K., Drake, J. F., de Wit, T. D., Eastwood, J. P., Ergun, R. E., Farrell, W. M., Fong, C., Goetz, K., Goldstein, M., Goodrich, K. A., Harvey, P. R., Horbury, T. S., Howes, G. G., Kasper, J. C., Kellogg, P. J., Klimchuk, J. A., Korreck, K. E., Krasnoselskikh, V. V., Krucker, S., Laker, R., Larson, D. E., MacDowall, R. J., Maksimovic, M., Malaspina, D. M., Martinez-Oliveros, J., McComas, D. J., Meyer-Vernet, N., Moncuquet, M., Mozer, F. S., Phan, T. D., Pulupa, M., Raouafi, N. E., Salem, C., Stansby, D., Stevens, M., Szabo, A., Velli, M., Woolley, T., and Wygant, J. R. (2019). Highly structured slow solar wind emerging from an equatorial coronal hole. *Nature*, 576(7786):237–242. (Cited on pages 18, 40, 116 and 156.)

- Bale, S. D., Drake, J. F., McManus, M. D., Desai, M. I., Badman, S. T., Larson, D. E., Swisdak, M., Horbury, T. S., Raouafi, N. E., Phan, T., Velli, M., McComas, D. J., Cohen, C. M. S., Mitchell, D., Panasenco, O., and Kasper, J. C. (2023). Interchange reconnection as the source of the fast solar wind within coronal holes. *Nature*, 618(7964):252–256. (Cited on page 148.)
- Bale, S. D., Goetz, K., Harvey, P. R., Turin, P., Bonnell, J. W., Dudok de Wit, T., Ergun, R. E., MacDowall, R. J., Pulupa, M., Andre, M., Bolton, M., Bougeret, J.-L., Bowen, T. A., Burgess, D., Cattell, C. A., Chandran, B. D. G., Chaston, C. C., Chen, C. H. K., Choi, M. K., Connerney, J. E., Cranmer, S., Diaz-Aguado, M., Donakowski, W., Drake, J. F., Farrell, W. M., Fergeau, P., Fermin, J., Fischer, J., Fox, N., Glaser, D., Goldstein, M., Gordon, D., Hanson, E., Harris, S. E., Hayes, L. M., Hinze, J. J., Hollweg, J. V., Horbury, T. S., Howard, R. A., Hoxie, V., Jannet, G., Karlsson, M., Kasper, J. C., Kellogg, P. J., Kien, M., Klimchuk, J. A., Krasnoselskikh, V. V., Krucker, S., Lynch, J. J., Maksimovic, M., Malaspina, D. M., Marker, S., Martin, P., Martinez-Oliveros, J., McCauley, J., McComas, D. J., McDonald, T., Meyer-Vernet, N., Moncuquet, M., Monson, S. J., Mozer, F. S., Murphy, S. D., Odom, J., Oliverson, R., Olson, J., Parker, E. N., Pankow, D., Phan, T., Quataert, E., Quinn, T., Ruplin, S. W., Salem, C., Seitz, D., Sheppard, D. A., Siy, A., Stevens, K., Summers, D., Szabo, A., Timofeeva, M., Vaivads, A., Velli, M., Yehle, A., Werthimer, D., and Wygant, J. R. (2016). The FIELDS Instrument Suite for Solar Probe Plus. *Space Science Reviews*, 204(1):49–82. (Cited on pages 16, 38 and 40.)
- Bale, S. D., Horbury, T. S., Velli, M., Desai, M. I., Halekas, J. S., McManus, M. D., Panasenco, O., Badman, S. T., Bowen, T. A., Chandran, B. D. G., Drake, J. F., Kasper, J. C., Laker, R., Mallet, A., Matteini, L., Phan, T. D., Raouafi, N. E., Squire, J., Woodham, L. D., and Woolley, T. (2021). A Solar Source of Alfvénic Magnetic Field Switchbacks: In Situ Remnants of Magnetic Funnels on Supergranulation Scales. *The Astrophysical Journal*, 923(2):174. (Cited on pages 26, 30, 71, 88 and 123.)
- Balogh, A., Forsyth, R. J., Lucek, E. A., Horbury, T. S., and Smith, E. J. (1999). Heliospheric magnetic field polarity inversions at high heliographic latitudes. *Geophysical Research Letters*, 26(6):631–634. (Cited on pages 11 and 18.)
- Bandyopadhyay, R., Matthaeus, W. H., McComas, D. J., Chhiber, R., Usmanov, A. V., Huang, J., Livi, R., Larson, D. E., Kasper, J. C., Case, A. W., Stevens, M., Whittlesey, P., Romeo, O. M., Bale, S. D., Bonnell, J. W., Dudok de Wit, T., Goetz, K., Harvey, P. R., MacDowall, R. J., Malaspina, D. M., and Pulupa, M. (2022). Sub-Alfvénic Solar Wind Observed by the Parker Solar Probe: Characterization of Turbulence, Anisotropy, Intermittency, and Switchback. *The Astrophysical Journal*, 926:L1. (Cited on page 140.)
- Barnes, A. (1976). On the nonexistence of plane-polarized large amplitude Alfvén

- waves. *Journal of Geophysical Research (1896-1977)*, 81(1):281–282. (Cited on page 53.)
- Barnes, A. (1981). Interplanetary Alfvénic fluctuations: A stochastic model. *Journal of Geophysical Research: Space Physics*, 86(A9):7498–7506. (Cited on page 54.)
- Baumjohann, W. and Treumann, R. (2012). *Basic Space Plasma Physics - Revised Edition*. (Cited on pages 8, 36 and 62.)
- Bemporad, A. (2017). Exploring the Inner Acceleration Region of Solar Wind: A Study Based on Coronagraphic UV and Visible Light Data. *The Astrophysical Journal*, 846(1):86. (Cited on page 16.)
- Benavitz, L. F., Boe, B., and Habbal, S. R. (2024). Total Solar Eclipse White-light Images as a Benchmark for Potential Field Source Surface Coronal Magnetic Field Models: An In-depth Analysis over a Solar Cycle. *The Astrophysical Journal*, 974(2):178. (Cited on page 144.)
- Biermann, L. (1963). *The Plasma in Interplanetary Space*. National Aeronautics and Space Administration. (Cited on page 5.)
- Bizien, N., Dudok De Wit, T., Froment, C., Velli, M., Case, A. W., Bale, S. D., Kasper, J., Whittlesey, P., MacDowall, R., and Larson, D. (2023). Are Switchback Boundaries Observed by Parker Solar Probe Closed? *The Astrophysical Journal*, 958(1):23. (Cited on pages 21, 31, 35, 38, 51, 52, 57, 58, 66 and 70.)
- Bizien, N., Froment, C., Madjarska, M. S., Dudok De Wit, T., and Velli, M. (2025). Tracing magnetic switchbacks to their source: An assessment of solar coronal jets as switchback precursors. *Astronomy & Astrophysics*, 694:A181. (Cited on pages 45, 125, 126, 127, 128, 129, 130, 131, 132, 134 and 136.)
- Boe, B., Habbal, S., and Druckmüller, M. (2020). Coronal Magnetic Field Topology from Total Solar Eclipse Observations. *The Astrophysical Journal*, 895(2):123. (Cited on page 144.)
- Brosius, A., Kane, T., and Verniero, J. (2024). Wave and Perturbation Polarization Techniques: Adaptive Minimum Variance Analysis (MVA) and Möbius Transformation. In *SHINE*. (Cited on page 77.)
- Brueckner, G. E., Howard, R. A., Koomen, M. J., Korendyke, C. M., Michels, D. J., Moses, J. D., Socker, D. G., Dere, K. P., Lamy, P. L., Llebaria, A., Bout, M. V., Schwenn, R., Simnett, G. M., Bedford, D. K., and Eyles, C. J. (1995). The Large Angle Spectroscopic Coronagraph (LASCO). *Solar Physics*, 162:357–402. (Cited on page 144.)
- Burlaga, L. F. and Ness, N. F. (1969). Tangential Discontinuities in the Solar Wind. *Solar Physics*, 9:467–477. (Cited on page 70.)

- Carlsson, M., De Pontieu, B., and Hansteen, V. H. (2019). New View of the Solar Chromosphere. *Annual Review of Astronomy and Astrophysics*, 57(1):189–226. (Cited on page 89.)
- Case, A. W., Kasper, J. C., Stevens, M. L., Korreck, K. E., Paulson, K., Daigneau, P., Caldwell, D., Freeman, M., Henry, T., Klingensmith, B., Bookbinder, J. A., Robinson, M., Berg, P., Tiu, C., Wright, K. H., Reinhart, M. J., Curtis, D., Ludlam, M., Larson, D., Whittlesey, P., Livi, R., Klein, K. G., and Martinović, M. M. (2020). The Solar Probe Cup on the Parker Solar Probe. *The Astrophysical Journal Supplement Series*, 246(2):43. (Cited on page 43.)
- Chaston, C. C., Bonnell, J. W., Bale, S. D., Kasper, J. C., Pulupa, M., Dudok de Wit, T., Bowen, T. A., Larson, D. E., Whittlesey, P. L., Wygant, J. R., Salem, C. S., MacDowall, R. J., Livi, R. L., Vech, D., Case, A. W., Stevens, M. L., Korreck, K. E., Goetz, K., Harvey, P. R., and Malaspina, D. M. (2020). MHD Mode Composition in the Inner Heliosphere from the Parker Solar Probe’s First Perihelion. *The Astrophysical Journal Supplement Series*, 246:71. (Cited on page 153.)
- Chen, J., Su, J., Yin, Z., Priya, T. G., Zhang, H., Liu, J., Xu, H., and Yu, S. (2015). Recurrent solar jets induced by a satellite spot and moving magnetic features. *The Astrophysical Journal*, 815(1):71. (Cited on pages 139 and 172.)
- Cheng, W., Liu, Y. D., Ran, H., Jiao, Y., Stevens, M. L., and Kasper, J. C. (2024). Origin and Properties of the Near-subsonic Solar Wind Observed by Parker Solar Probe. *The Astrophysical Journal*, 967(1):58. (Cited on page 140.)
- Chitta, L. P., Zhukov, A. N., Berghmans, D., Peter, H., Parenti, S., Mandal, S., Aznar Cuadrado, R., Schühle, U., Teriaca, L., Auchère, F., Barczynski, K., Buchlin, , Harra, L., Kraaikamp, E., Long, D. M., Rodriguez, L., Schwanitz, C., Smith, P. J., Verbeeck, C., and Seaton, D. B. (2023). Picoflare jets power the solar wind emerging from a coronal hole on the Sun. *Science*, 381(6660):867–872. (Cited on pages 89, 90 and 133.)
- Choi, K.-E., Agapitov, O., Colombari, L., Bonnell, J. W., Mozer, F., Sydora, R. D., Raouafi, N., and Wit, T. D. d. (2024). Whistler Waves in the Young Solar Wind: Statistics of Amplitude and Propagation Direction from Parker Solar Probe Encounters 1–11. *The Astrophysical Journal*, 971(2):177. (Cited on page 80.)
- Cirtain, J. W., Golub, L., Lundquist, L., van Ballegoijen, A., Savcheva, A., Shimojo, M., DeLuca, E., Tsuneta, S., Sakao, T., Reeves, K., Weber, M., Kano, R., Narukage, N., and Shibasaki, K. (2007). Evidence for Alfvén Waves in Solar X-ray Jets. *Science*, 318(5856):1580–1582. (Cited on pages 87, 94, 139 and 162.)
- Collier, M. R., Szabo, A., Farrell, W. M., Slavin, J. A., Lepping, R. P., Fitzenreiter, R., Thompson, B., Hamilton, D. C., Gloeckler, G., Ho, G. C., Bochsler, P., Larson, D., and Ofman, L. (2001). Reconnection remnants in the magnetic cloud of October

- 18–19, 1995: A shock, monochromatic wave, heat flux dropout, and energetic ion beam. *Journal of Geophysical Research: Space Physics*, 106(A8):15985–16000. (Cited on page 122.)
- Community, T. S., Barnes, W. T., Bobra, M. G., Christe, S. D., Freij, N., Hayes, L. A., Ireland, J., Mumford, S., Perez-Suarez, D., Ryan, D. F., Shih, A. Y., Contributors), P. P., Chanda, P., Glogowski, K., Hewett, R., Hughitt, V. K., Hill, A., Hiware, K., Inglis, A., Kirk, M. S. F., Konge, S., Mason, J. P., Maloney, S. A., Murray, S. A., Panda, A., Park, J., Pereira, T. M. D., Reardon, K., Savage, S., Sipőcz, B. M., Stansby, D., Jain, Y., Taylor, G., Yadav, T., Rajul, Dang, T. K., and Contributors), S. (2020). The SunPy Project: Open Source Development and Status of the Version 1.0 Core Package. *The Astrophysical Journal*, 890(1):68. (Cited on page 169.)
- Cranmer, S. R., Asgari-Targhi, M., Miralles, M. P., Raymond, J. C., Strachan, L., Tian, H., and Woolsey, L. N. (2015). The role of turbulence in coronal heating and solar wind expansion. *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences*, 373(2041):20140148. (Cited on page 16.)
- Cranmer, S. R., Gibson, S. E., and Riley, P. (2017). Origins of the Ambient Solar Wind: Implications for Space Weather. *Space Science Reviews*, 212:1345–1384. (Cited on page 14.)
- Crooker, N. U., Gosling, J. T., and Kahler, S. W. (2002). Reducing heliospheric magnetic flux from coronal mass ejections without disconnection. *Journal of Geophysical Research: Space Physics*, 107(A2):SSH 3–1–SSH 3–5. (Cited on pages 14, 29 and 157.)
- Dakeyo, J.-B., Badman, S. T., Rouillard, A. P., Réville, V., Verscharen, D., Démoulin, P., and Maksimovic, M. (2024). Radial evolution of the accuracy of ballistic solar wind backmapping. *Astronomy & Astrophysics*, 686:A12. (Cited on page 102.)
- Dakeyo, J.-B., Maksimovic, M., Démoulin, P., Halekas, J., and Stevens, M. L. (2022). Statistical Analysis of the Radial Evolution of the Solar Winds between 0.1 and 1 au and Their Semiempirical Isopoly Fluid Modeling. *The Astrophysical Journal*, 940(2):130. (Cited on pages 15 and 121.)
- de Pablos, D., Samanta, T., Badman, S. T., Schwanitz, C., Bahauddin, S. M., Harra, L. K., Petrie, G., Mac Cormack, C., Mandrini, C. H., Raouafi, N. E., Martinez Pillet, V., and Velli, M. (2022). Searching for a Solar Source of Magnetic-Field Switchbacks in Parker Solar Probe’s First Encounter. *Solar Physics*, 297(7):90. (Cited on pages 116 and 151.)
- DeForest, C. E., Howard, R. A., Velli, M., Viall, N., and Vourlidas, A. (2018). The Highly Structured Outer Solar Corona. *The Astrophysical Journal*, 862:18. (Cited on page 145.)

- Denskat, K. U. and Burlaga, L. F. (1977). Multispacecraft observations of microscale fluctuations in the solar wind. *Journal of Geophysical Research*, 82(19):2693–2704. (Cited on page 79.)
- DeVore, C. R. and Antiochos, S. K. (2008). Homologous Confined Filament Eruptions via Magnetic Breakout. *The Astrophysical Journal*, 680:740–756. (Cited on page 153.)
- Dolliou, A., Parenti, S., Auchère, F., Bocchialini, K., Pelouze, G., Antolin, P., Berghmans, D., Harra, L., Long, D. M., Schühle, U., Kraaikamp, E., Stegen, K., Verbeeck, C., Gissot, S., Aznar Cuadrado, R., Buchlin, E., Mierla, M., Teriaca, L., and Zhukov, A. N. (2023). Temperature of quiet Sun small scale brightenings observed by EUI on board Solar Orbiter: Evidence for a cooler component. *Astronomy & Astrophysics*, 671:A64. (Cited on page 97.)
- Domingo, V., Fleck, B., and Poland, A. I. (1995). The SOHO Mission: an Overview. *Solar Physics*, 162:1–37. (Cited on page 144.)
- Doschek, G. A., Landi, E., Warren, H. P., and Harra, L. K. (2010). Bright points and jets in polar coronal holes observed by the Extreme ultraviolet imaging spectrometer on Hinode. *The Astrophysical Journal*, 710(2):1806. (Cited on page 91.)
- Doss, C. E., Cassak, P. A., and Swisdak, M. (2016). Particle-in-cell simulation study of the scaling of asymmetric magnetic reconnection with in-plane flow shear. *Physics of Plasmas*, 23(8):082107. (Cited on page 80.)
- Drake, J. F., Agapitov, O., Swisdak, M., Badman, S. T., Bale, S. D., Horbury, T. S., Kasper, J. C., MacDowall, R. J., Mozer, F. S., Phan, T. D., Pulupa, M., Szabo, A., and Velli, M. (2021). Switchbacks as signatures of magnetic flux ropes generated by interchange reconnection in the corona. *Astronomy & Astrophysics*, 650:A2. (Cited on page 29.)
- Druckmüller, M. (2013). A Nois Adaptive Fuzzy Equalization method for processing solar Extreme Ultraviolet Images. *The Astrophysical Journal Supplement Series*, 207(2):25. (Cited on page 167.)
- Dudok de Wit, T., Krasnoselskikh, V. V., Bale, S. D., Bonnell, J. W., Bowen, T. A., Chen, C. H. K., Froment, C., Goetz, K., Harvey, P. R., Jagarlamudi, V. K., Larosa, A., MacDowall, R. J., Malaspina, D. M., Matthaeus, W. H., Pulupa, M., Velli, M., and Whittlesey, P. L. (2020). Switchbacks in the Near-Sun Magnetic Field: Long Memory and Impact on the Turbulence Cascade. *The Astrophysical Journal Supplement Series*, 246(2):39. (Cited on pages 21, 40, 41, 71 and 161.)
- Dudok De Wit, T., x, and x (2024). in prep. (Cited on pages 26, 28 and 44.)
- Dunlop, M. W. and Woodward, T. I. (1998). Multi-Spacecraft Discontinuity Analysis: Orientation and Motion. *ISSI Scientific Reports Series*, 1:271–306. (Cited on page 77.)

- Fargette, N., Lavraud, B., Rouillard, A. P., Réville, V., Bale, S. D., and Kasper, J. (2022). The preferential orientation of magnetic switchbacks and its implications for solar magnetic flux transport. *Astronomy & Astrophysics*, 663:A109. (Cited on pages 25, 59 and 151.)
- Fargette, N., Lavraud, B., Rouillard, A. P., Réville, V., Dudok De Wit, T., Froment, C., Halekas, J. S., Phan, T. D., Malaspina, D. M., Bale, S. D., Kasper, J. C., Louarn, P., Case, A. W., Korreck, K. E., Larson, D. E., Pulupa, M., Stevens, M. L., Whittlesey, P. L., and Berthomier, M. (2021). Characteristic Scales of Magnetic Switchback Patches Near the Sun and Their Possible Association With Solar Supergranulation and Granulation. *The Astrophysical Journal*, 919(2):96. (Cited on pages 26, 40, 88, 137 and 148.)
- Farrell, W. M., MacDowall, R. J., Gruesbeck, J. R., Bale, S. D., and Kasper, J. C. (2020). Magnetic Field Dropouts at Near-Sun Switchback Boundaries: A Superposed Epoch Analysis. *The Astrophysical Journal Supplement Series*, 249(2):28. (Cited on pages 25, 46, 78, 150 and 156.)
- Farrell, W. M., Rasca, A. P., MacDowall, R. J., Gruesbeck, J. R., Bale, S. D., and Kasper, J. C. (2021). Switchback Boundary Dissipation and Relative Age. *The Astrophysical Journal*, 915(1):68. (Cited on page 80.)
- Feldman, W. C., Asbridge, J. R., Bame, S. J., Montgomery, M. D., and Gary, S. P. (1975). Solar wind electrons. *Journal of Geophysical Research (1896-1977)*, 80(31):4181–4196. (Cited on page 20.)
- Fisk, L. A. and Kasper, J. C. (2020). Global Circulation of the Open Magnetic Flux of the Sun. *The Astrophysical Journal Letters*, 894(1):L4. (Cited on pages 29, 87 and 161.)
- Fox, N. J., Velli, M. C., Bale, S. D., Decker, R., Driesman, A., Howard, R. A., Kasper, J. C., Kinnison, J., Kusterer, M., Lario, D., Lockwood, M. K., McComas, D. J., Raouafi, N. E., and Szabo, A. (2016). The Solar Probe Plus Mission: Humanity’s First Visit to Our Star. *Space Science Reviews*, 204(1):7–48. (Cited on pages 16, 17 and 156.)
- Froment, C., Krasnoselskikh, V., de Wit, T. D., Agapitov, O., Fargette, N., Lavraud, B., Larosa, A., Kretzschmar, M., Jagarlamudi, V. K., Velli, M., Malaspina, D., Whittlesey, P. L., Bale, S. D., Case, A. W., Goetz, K., Kasper, J. C., Korreck, K. E., Larson, D. E., MacDowall, R. J., Mozer, F. S., Pulupa, M., Revillet, C., and Stevens, M. L. (2021). Direct evidence for magnetic reconnection at the boundaries of magnetic switchbacks with Parker Solar Probe. *Astronomy & Astrophysics*, 650:A5. (Cited on pages 31, 79 and 153.)
- Gary, G. A. (2001). Plasma Beta above a Solar Active Region: Rethinking the Paradigm. *Solar Physics*, 203(1):71–86. (Cited on page 4.)

- Golub, G. H. and Loan, C. F. V. (2013). *Matrix Computations*. Johns Hopkins University Press. (Cited on page 56.)
- Golub, L., Krieger, A. S., Silk, J. K., Timothy, A. F., and Vaiana, G. S. (1974). Solar X-Ray Bright Points. *The Astrophysical Journal*, 189:L93. (Cited on page 93.)
- Gosling, J. T., Skoug, R. M., McComas, D. J., and Smith, C. W. (2005). Direct evidence for magnetic reconnection in the solar wind near 1 AU. *Journal of Geophysical Research: Space Physics*, 110(A1):2004JA010809. (Cited on page 79.)
- Graham, G. A., Rae, I. J., Owen, C. J., Walsh, A. P., Arridge, C. S., Gilbert, L., Lewis, G. R., Jones, G. H., Forsyth, C., Coates, A. J., and Waite, J. H. (2017). The evolution of solar wind strahl with heliospheric distance. *Journal of Geophysical Research: Space Physics*, 122(4):3858–3874. (Cited on page 20.)
- Gringauz, K. I. (1963). The structure of the ionized gas envelope of earth from direct measurements in the U.S.S.R. of local charged particle concentrations. *Planetary and Space Science*, 11(3):281–296. (Cited on page 6.)
- Gringauz, K. I., Bezrukikh, V. V., Ozerov, V. D., and Rybchinskii, R. E. (1962). The study of interplanetary ionized gas, high-energy electrons and corpuscular radiation of the sun, employing three-electrode charged particle traps on the second Soviet space rocket. *Planetary and Space Science*, 9(3):103–107. (Cited on page 6.)
- Haaland, S. and Paschmann, G. (2001). Improved Boundary Normal Calculations Using Minimum Variance Analysis and Wavelet De-Noising Techniques. *Sheffield Space Plasma Meeting*, 492:127. (Cited on page 47.)
- Haaland, S., Sonnerup, B., and Paschmann, G. (2012). More about arc-polarized structures in the solar wind. *Annales Geophysicae*, 30(5):867–883. (Cited on page 53.)
- Habbal, S. R., Druckmüller, M., Alzate, N., Ding, A., Johnson, J., Starha, P., Hoderova, J., Boe, B., Constantinou, S., and Arndt, M. (2021). Identifying the Coronal Source Regions of Solar Wind Streams from Total Solar Eclipse Observations and in situ Measurements Extending over a Solar Cycle. *The Astrophysical Journal Letters*, 911(1):L4. (Cited on page 2.)
- Hagenaar, H. J., Schrijver, C. J., and Title, A. M. (2003). The Properties of Small Magnetic Regions on the Solar Surface and the Implications for the Solar Dynamo(s). *The Astrophysical Journal*, 584(2):1107. (Cited on page 109.)
- Hanaoka, Y., Hasuo, R., Hirose, T., Ikeda, A. C., Ishibashi, T., Manago, N., Masuda, Y., Morita, S., Nakazawa, J., Ohgoe, O., Sakai, Y., Sasaki, K., Takahashi, K., and Toi, T. (2018). Solar Coronal Jets Extending to High Altitudes Observed during the 2017 August 21 Total Eclipse. *The Astrophysical Journal*, 860(2):142. (Cited on pages 94 and 139.)

- Hanson, E. L. M., Agapitov, O. V., Mozer, F. S., Krasnoselskikh, V., Bale, S. D., Avanov, L., Khotyaintsev, Y., and Giles, B. (2019). Cross-Shock Potential in Rippled Versus Planar Quasi-Perpendicular Shocks Observed by MMS. *Geophysical Research Letters*, 46(5):2381–2389. (Cited on page 77.)
- Harvey, J. W., Hill, F., Hubbard, R. P., Kennedy, J. R., Leibacher, J. W., Pintar, J. A., Gilman, P. A., Noyes, R. W., Title, A. M., Toomre, J., Ulrich, R. K., Bhatnagar, A., Kennewell, J. A., Marquette, W., Patrón, J., Saá, O., and Yasukawa, E. (1996). The Global Oscillation Network Group (GONG) Project. *Science*, 272(5266):1284–1286. (Cited on page 107.)
- Hausman, B. A., Michel, F. C., Espley, J. R., and Cloutier, P. A. (2004). On determining the nature and orientation of magnetic directional discontinuities: Problems with the minimum variance method. *Journal of Geophysical Research: Space Physics*, 109(A11). (Cited on page 53.)
- Hayashi, K., Yang, S., and Deng, Y. (2016). Comparison of potential field solutions for Carrington Rotation 2144. *Journal of Geophysical Research: Space Physics*, 121(2):1046–1061. (Cited on page 108.)
- He, J., Zhu, X., Yang, L., Hou, C., Duan, D., Zhang, L., and Wang, Y. (2021). Solar Origin of Compressive Alfvénic Spikes/Kinks as Observed by Parker Solar Probe. *The Astrophysical Journal Letters*, 913(1):L14. (Cited on page 153.)
- Heinemann, S. G., Jerčić, V., Temmer, M., Hofmeister, S. J., Dumbović, M., Vernerstrom, S., Verbanac, G., and Veronig, A. M. (2020). A statistical study of the long-term evolution of coronal hole properties as observed by SDO. *Astronomy & Astrophysics*, 638:A68. (Cited on page 92.)
- Higginson, A. K. and Lynch, B. J. (2018). Structured Slow Solar Wind Variability: Streamer-blob Flux Ropes and Torsional Alfvén Waves. *The Astrophysical Journal*, 859(1):6. (Cited on page 14.)
- Hoeksema, J. T. (1984). *Structure and Evolution of the Large Scale Solar and Heliospheric Magnetic Fields*. PhD thesis. (Cited on page 109.)
- Horbury, T. S., Burgess, D., Fränz, M., and Owen, C. J. (2001). Three spacecraft observations of solar wind discontinuities. *Geophysical Research Letters*, 28(4):677–680. (Cited on pages 55, 65 and 70.)
- Horbury, T. S., Matteini, L., and Stansby, D. (2018). Short, large-amplitude speed enhancements in the near-Sun solar wind. *Monthly Notices of the Royal Astronomical Society*, 478(2):1980–1986. (Cited on pages 18 and 19.)
- Horbury, T. S., Woolley, T., Laker, R., Matteini, L., Eastwood, J., Bale, S. D., Velli, M., Chandran, B. D. G., Phan, T., Raouafi, N. E., Goetz, K., Harvey, P. R., Pulupa, M., Klein, K. G., Wit, T. D. d., Kasper, J. C., Korreck, K. E., Case, A. W., Stevens,

- M. L., Whittlesey, P., Larson, D., MacDowall, R. J., Malaspina, D. M., and Livi, R. (2020). Sharp Alfvénic Impulses in the Near-Sun Solar Wind. *The Astrophysical Journal Supplement Series*, 246(2):45. (Cited on pages 23, 37 and 40.)
- Hortin, T. (2003). *Héliométrie chromosphérique et coronale*. Thèse de doctorat, Université Paris-Sud, 1970-2019, France. (Cited on page 117.)
- Hou, C., He, J., Duan, D., Wu, Z., Chen, Y., Verscharen, D., Rouillard, A. P., Li, H., Yang, L., and Bale, S. D. (2024a). The origin of interplanetary switchbacks in reconnection at chromospheric network boundaries. *Nature Astronomy*, pages 1–11. (Cited on pages 137, 150 and 152.)
- Hou, C., Rouillard, A. P., He, J., Gannouni, B., Réville, V., Louarn, P., Fedorov, A., Přech, L., Owen, C. J., Verscharen, D., D’Amicis, R., Sorriso-Valvo, L., Fargette, N., Coburn, J., Génot, V., Raines, J. M., Bruno, R., Livi, S., Lavraud, B., André, N., Fruit, G., Kieokaew, R., Plotnikov, I., Penou, E., Barthe, A., Kataria, D., Berthomier, M., Allegrini, F., Fortunato, V., Mele, G., and Horbury, T. (2024b). Connecting Solar Wind Velocity Spikes Measured by Solar Orbiter and Coronal Brightenings Observed by SDO. *The Astrophysical Journal Letters*, 968(2):L28. (Cited on pages 142 and 152.)
- Howard, T. A. and Tappin, S. J. (2009). Interplanetary Coronal Mass Ejections Observed in the Heliosphere: 1. Review of Theory. *Space Science Reviews*, 147(1):31–54. (Cited on page 144.)
- Huang, J., Kasper, J. C., Fisk, L. A., Larson, D. E., McManus, M. D., Chen, C. H. K., Martinović, M. M., Klein, K. G., Thomas, L., Liu, M., Maruca, B. A., Zhao, L., Chen, Y., Hu, Q., Jian, L. K., Verniero, J. L., Velli, M., Livi, R., Whittlesey, P., Rahmati, A., Romeo, O., Niembro, T., Paulson, K., Stevens, M., Case, A. W., Pulupa, M., Bale, S. D., and Halekas, J. S. (2023a). The Structure and Origin of Switchbacks: Parker Solar Probe Observations. *The Astrophysical Journal*, 952(1):33. (Cited on pages 73, 80, 81, 143 and 151.)
- Huang, N., D’Anna, S., and Wang, H. (2023b). Statistical Study of Ejections in Coronal Hole Regions As Possible Sources of Solar Wind Switchbacks and Small-scale Magnetic Flux Ropes. *The Astrophysical Journal Letters*, 946(1):L17. (Cited on pages 89, 133 and 147.)
- Hudson, P. D. (1970). Discontinuities in an anisotropic plasma and their identification in the solar wind. *Planetary and Space Science*, 18(11):1611–1622. (Cited on pages 35 and 36.)
- Jagarlamudi, V. K., Raouafi, N. E., Bourouaine, S., Mostafavi, P., Larosa, A., and Perez, J. C. (2023). Occurrence and Evolution of Switchbacks in the Inner Heliosphere: Parker Solar Probe Observations. *The Astrophysical Journal Letters*, 950(1):L7. (Cited on pages 28 and 151.)

- Jannet, G., Dudok de Wit, T., Krasnoselskikh, V., Kretzschmar, M., Ferreau, P., Bergerard-Timofeeva, M., Agrapart, C., Brochot, J.-Y., Chalumeau, G., Martin, P., Reville, C., Bale, S. D., Maksimovic, M., Bowen, T. A., Brysbaert, C., Goetz, K., Guilhem, E., Harvey, P. R., Leray, V., and Lorfèvre, E. (2021). Measurement of Magnetic Field Fluctuations in the Parker Solar Probe and Solar Orbiter Missions. *Journal of Geophysical Research: Space Physics*, 126(2):e2020JA028543. (Cited on page 17.)
- Janse, M., Low, B. C., and Parker, E. N. (2010). Topological complexity and tangential discontinuity in magnetic fields. *Physics of Plasmas*, 17(9):092901. (Cited on page 80.)
- Jarolim, R., Tremblay, B., Rempel, M., Molnar, M., Veronig, A. M., Thalmann, J. K., and Podladchikova, T. (2024). Advancing Solar Magnetic Field Extrapolations through Multiheight Magnetic Field Measurements. *The Astrophysical Journal Letters*, 963(1):L21. (Cited on page 142.)
- Kamio, S., Curdt, W., Teriaca, L., and Innes, D. E. (2011). Evolution of microflares associated with bright points in coronal holes and in quiet regions. *Astronomy & Astrophysics*, 529:A21. (Cited on page 93.)
- Kasper, J. C., Abiad, R., Austin, G., Balat-Pichelin, M., Bale, S. D., Belcher, J. W., Berg, P., Bergner, H., Berthomier, M., Bookbinder, J., Brodu, E., Caldwell, D., Case, A. W., Chandran, B. D. G., Cheimets, P., Cirtain, J. W., Cranmer, S. R., Curtis, D. W., Daigneau, P., Dalton, G., Dasgupta, B., DeTomaso, D., Diaz-Aguado, M., Djordjevic, B., Donaskowski, B., Effinger, M., Florinski, V., Fox, N., Freeman, M., Gallagher, D., Gary, S. P., Gauron, T., Gates, R., Goldstein, M., Golub, L., Gordon, D. A., Gurnee, R., Guth, G., Halekas, J., Hatch, K., Heerikuisen, J., Ho, G., Hu, Q., Johnson, G., Jordan, S. P., Korreck, K. E., Larson, D., Lazarus, A. J., Li, G., Livi, R., Ludlam, M., Maksimovic, M., McFadden, J. P., Marchant, W., Maruca, B. A., McComas, D. J., Messina, L., Mercer, T., Park, S., Peddie, A. M., Pogorelov, N., Reinhart, M. J., Richardson, J. D., Robinson, M., Rosen, I., Skoug, R. M., Slagle, A., Steinberg, J. T., Stevens, M. L., Szabo, A., Taylor, E. R., Tiu, C., Turin, P., Velli, M., Webb, G., Whittlesey, P., Wright, K., Wu, S. T., and Zank, G. (2016). Solar Wind Electrons Alphas and Protons (SWEAP) Investigation: Design of the Solar Wind and Coronal Plasma Instrument Suite for Solar Probe Plus. *Space Science Reviews*, 204:131–186. (Cited on pages 16 and 43.)
- Kasper, J. C., Bale, S. D., Belcher, J. W., Berthomier, M., Case, A. W., Chandran, B. D. G., Curtis, D. W., Gallagher, D., Gary, S. P., Golub, L., Halekas, J. S., Ho, G. C., Horbury, T. S., Hu, Q., Huang, J., Klein, K. G., Korreck, K. E., Larson, D. E., Livi, R., Maruca, B., Lavraud, B., Louarn, P., Maksimovic, M., Martinovic, M., McGinnis, D., Pogorelov, N. V., Richardson, J. D., Skoug, R. M., Steinberg, J. T., Stevens, M. L., Szabo, A., Velli, M., Whittlesey, P. L., Wright, K. H., Zank, G. P., MacDowall, R. J., McComas, D. J., McNutt, R. L., Pulupa, M., Raouafi,

- N. E., and Schwadron, N. A. (2019). Alfvénic velocity spikes and rotational flows in the near-Sun solar wind. *Nature*, 576(7786):228–231. (Cited on pages 18, 21, 25, 27, 37, 67, 135 and 156.)
- Kawano, H. and Higuchi, T. (1995). The bootstrap method in space physics: Error estimation for the minimum variance analysis. *Geophysical Research Letters*, 22(3):307–310. (Cited on page 55.)
- Kennis, S., Perri, B., and Poedts, S. (2024). Magnetic connectivity from the Sun to the Earth with MHD models. I. Impact of the magnetic modelling on connectivity validation. *Astronomy & Astrophysics*. (Cited on page 142.)
- Khrabrov, A. V. and Sonnerup, B. U. (1998). Error estimates for minimum variance analysis. *Journal of Geophysical Research*, 103:6641–6652. (Cited on page 55.)
- Knetter, T. (2005). *A new Perspective of the Solar Wind Micro-Structure due to Multi-Point Observations of Discontinuities*. PhD thesis, Universität zu Köln. (Cited on pages 65 and 72.)
- Knetter, T., Neubauer, F. M., Horbury, T., and Balogh, A. (2003). Discontinuity observations with cluster. *Advances in Space Research*, 32(4):543–548. (Cited on pages 70 and 150.)
- Knetter, T., Neubauer, F. M., Horbury, T., and Balogh, A. (2004). Four-point discontinuity observations using Cluster magnetic field data: A statistical survey. *Journal of Geophysical Research: Space Physics*, 109(A6). (Cited on pages 55 and 70.)
- Koukras, A., Dolla, L., and Keppens, R. (2022). Estimating uncertainties in the back-mapping of the fast solar wind. (Cited on pages 97, 98, 102, 109, 113, 120, 121, 122, 123, 135 and 163.)
- Krasnoselskikh, V., Larosa, A., Agapitov, O., de Wit, T. D., Moncuquet, M., Mozer, F. S., Stevens, M., Bale, S. D., Bonnell, J., Froment, C., Goetz, K., Goodrich, K., Harvey, P., Kasper, J., MacDowall, R., Malaspina, D., Pulupa, M., Raouafi, N., Revillet, C., Velli, M., and Wygant, J. (2020). Localized Magnetic-field Structures and Their Boundaries in the Near-Sun Solar Wind from Parker Solar Probe Measurements. *The Astrophysical Journal*, 893(2):93. (Cited on pages 29, 31, 47 and 80.)
- Kumar, P., Karpen, J. T., Uritsky, V. M., Deforest, C. E., Raouafi, N. E., DeVore, C. R., and Antiochos, S. K. (2023). New Evidence on the Origin of Solar Wind Microstreams/Switchbacks. *The Astrophysical Journal Letters*, 951(1):L15. (Cited on pages 151 and 152.)
- Laker, R., Horbury, T. S., Bale, S. D., Matteini, L., Woolley, T., Woodham, L. D., Badman, S. T., Pulupa, M., Kasper, J. C., Stevens, M., Case, A. W., and Korreck, K. E. (2021). Statistical analysis of orientation, shape, and size of solar wind switchbacks. *Astronomy & Astrophysics*, 650:A1. (Cited on pages 23, 25, 59 and 154.)

- Laker, R., Horbury, T. S., Matteini, L., Bale, S. D., Stawarz, J. E., Woodham, L. D., and Woolley, T. (2022). Switchback deflections beyond the early parker solar probe encounters. *Monthly Notices of the Royal Astronomical Society*, 517(1):1001–1005. (Cited on pages 25 and 67.)
- Larosa, A., Krasnoselskikh, V., Wit, T. D. d., Agapitov, O., Froment, C., Jagarlamudi, V. K., Velli, M., Bale, S. D., Case, A. W., Goetz, K., Harvey, P., Kasper, J. C., Korreck, K. E., Larson, D. E., MacDowall, R. J., Malaspina, D., Pulupa, M., Revillet, C., and Stevens, M. L. (2021). Switchbacks: statistical properties and deviations from Alfvénicity. *Astronomy & Astrophysics*, 650:A3. (Cited on pages 25, 31, 40, 46, 67, 68, 69, 72, 78, 80, 150, 153 and 156.)
- Lee, E. J., Archontis, V., and Hood, A. W. (2014). Helical blowout jets in the Sun: Untwisting and propagation of waves. *The Astrophysical Journal Letters*, 798(1):L10. (Cited on pages 87 and 161.)
- Lee, J., Wang, H., Wang, J., and Wang, M. (2024). Solar Spicules, Filigrees, and Solar Wind Switchbacks. *The Astrophysical Journal*, 963(2):79. (Cited on page 148.)
- Leighton, R. B., Noyes, R. W., and Simon, G. W. (1962). Velocity Fields in the Solar Atmosphere. I. Preliminary Report. *The Astrophysical Journal*, 135:474. (Cited on page 88.)
- Lemen, J. R., Title, A. M., Akin, D. J., Boerner, P. F., Chou, C., Drake, J. F., Duncan, D. W., Edwards, C. G., Friedlaender, F. M., Heyman, G. F., Hurlburt, N. E., Katz, N. L., Kushner, G. D., Levay, M., Lindgren, R. W., Mathur, D. P., McFeaters, E. L., Mitchell, S., Rehse, R. A., Schrijver, C. J., Springer, L. A., Stern, R. A., Tarbell, T. D., Wuelser, J.-P., Wolfson, C. J., Yanari, C., Bookbinder, J. A., Cheimets, P. N., Caldwell, D., Deluca, E. E., Gates, R., Golub, L., Park, S., Podgorski, W. A., Bush, R. I., Scherrer, P. H., Gumm, M. A., Smith, P., Auken, G., Jerram, P., Pool, P., Soufli, R., Windt, D. L., Beardsley, S., Clapp, M., Lang, J., and Waltham, N. (2012). The Atmospheric Imaging Assembly (AIA) on the Solar Dynamics Observatory (SDO). *Solar Physics*, 275(1):17–40. (Cited on page 96.)
- Lepping, R. and Behannon, K. (1980). Magnetic field directional discontinuities: 1. Minimum variance errors. *Journal of Geophysical Research: Space Physics*, 85(A9):4695–4703. (Cited on page 55.)
- Lin, C. C., Tsai, C. L., Chen, H. J., Weng, C. J., Chao, J. K., and Lee, L. C. (2009). A possible generation mechanism of interplanetary rotational discontinuities. *Journal of Geophysical Research: Space Physics*, 114(A8). (Cited on page 80.)
- Lionello, R., Török, T., Titov, V. S., Leake, J. E., Mikić, Z., Linker, J. A., and Linton, M. G. (2016). The contribution of Coronal Jets to the Solar Wind. *The Astrophysical Journal Letters*, 831(1):L2. (Cited on page 135.)

- Liu, R., Liu, Y. C.-M., Huang, J., Huang, Z., Klecker, B., and Wang, C. (2022a). Density Compressions at Magnetic Switchbacks Associated With Fast Plasma: A Superposed Epoch Analysis. *Journal of Geophysical Research: Space Physics*, 127(5):e2022JA030382. (Cited on page 74.)
- Liu, Y. Y., Fu, H. S., Cao, J. B., Yu, Y., Liu, C. M., Wang, Z., Guo, Z. Z., and He, R. J. (2022b). Categorizing MHD Discontinuities in the Inner Heliosphere by Utilizing the PSP Mission. *Journal of Geophysical Research: Space Physics*, 127(3):e2021JA029983. (Cited on page 44.)
- Livi, R., Larson, D. E., Kasper, J. C., Abiad, R., Case, A. W., Klein, K. G., Curtis, D. W., Dalton, G., Stevens, M., Korreck, K. E., Ho, G., Robinson, M., Tiu, C., Whittlesey, P. L., Verniero, J. L., Halekas, J., McFadden, J., Marckwordt, M., Slagle, A., Abatcha, M., Rahmati, A., and McManus, M. D. (2022). The Solar Probe ANalyzer—Ions on the Parker Solar Probe. *The Astrophysical Journal*, 938(2):138. (Cited on page 43.)
- Mackay, D. H. and Yeates, A. R. (2012). The Sun’s Global Photospheric and Coronal Magnetic Fields: Observations and Models. *Living Reviews in Solar Physics*, 9. (Cited on pages 104 and 105.)
- Madjarska, M. S. (2011). Dynamics and plasma properties of an X-ray jet from SUMER, EIS, XRT, and EUVI A & B simultaneous observations. *Astronomy & Astrophysics*, 526:A19. (Cited on pages 93, 139 and 172.)
- Madjarska, M. S. (2019). Coronal bright points. *Living Reviews in Solar Physics*, 16(1):2. (Cited on pages 11, 89, 90, 91 and 162.)
- Madjarska, M. S., Doyle, J. G., Teriaca, L., and Banerjee, D. (2003). An EUV Bright Point as seen by SUMER, CDS, MDI and EIT on-board SoHO. *Astronomy & Astrophysics*, 398(2):775–784. (Cited on page 91.)
- Malaspina, D. M., Chasapis, A., Tatum, P., Salem, C., Bale, S. D., Bonnell, J. W., Wit, T. D. d., Goetz, K., Pulupa, M., Halekas, J., Whittlesey, P., Livi, R., Case, A. W., Stevens, M. L., and Larson, D. (2022). Inhomogeneous Kinetic Alfvén Waves in the Near-Sun Solar Wind. *The Astrophysical Journal*, 936(2):128. (Cited on pages 47 and 80.)
- Mariani, F., Bavassano, B., and Villante, U. (1983). A Statistical Study of Magnetohydrodynamic Discontinuities in the Inner Solar System - HELIOS-1 and HELIOS-2. *Solar Physics*, 83:349–365. (Cited on page 150.)
- Matteini, L., Horbury, T. S., Neugebauer, M., and Goldstein, B. E. (2014). Dependence of solar wind speed on the local magnetic field orientation: Role of Alfvénic fluctuations. *Geophysical Research Letters*, 41(2):259–265. (Cited on pages 25, 63, 79 and 156.)

- McComas, D. J., Alexander, N., Angold, N., Bale, S., Beebe, C., Birdwell, B., Boyle, M., Burgum, J. M., Burnham, J. A., Christian, E. R., Cook, W. R., Cooper, S. A., Cummings, A. C., Davis, A. J., Desai, M. I., Dickinson, J., Dirks, G., Do, D. H., Fox, N., Giacalone, J., Gold, R. E., Gurnee, R. S., Hayes, J. R., Hill, M. E., Kasper, J. C., Kecman, B., Klemic, J., Krimigis, S. M., Labrador, A. W., Layman, R. S., Leske, R. A., Livi, S., Matthaeus, W. H., McNutt, R. L., Mewaldt, R. A., Mitchell, D. G., Nelson, K. S., Parker, C., Rankin, J. S., Roelof, E. C., Schwadron, N. A., Seifert, H., Shuman, S., Stokes, M. R., Stone, E. C., Vandegriff, J. D., Velli, M., von Rosenvinge, T. T., Weidner, S. E., Wiedenbeck, M. E., and Wilson, P. (2016). Integrated Science Investigation of the Sun (ISIS): Design of the Energetic Particle Investigation. *Space Science Reviews*, 204(1):187–256. (Cited on page 17.)
- McComas, D. J., Ebert, R. W., Elliott, H. A., Goldstein, B. E., Gosling, J. T., Schwadron, N. A., and Skoug, R. M. (2008). Weaker solar wind from the polar coronal holes and the whole Sun. *Geophysical Research Letters*, 35(18). (Cited on page 12.)
- McCracken, K. G. and Ness, N. F. (1966). The Collimation of Cosmic Rays by the Interplanetary Magnetic Field. *Journal of Geophysical Research*, 71(13):3315–3318. (Cited on pages 18 and 19.)
- Miles, D. M., Narod, B. B., Milling, D. K., Mann, I. R., Barona, D., and Hospodarsky, G. B. (2018). A hybrid fluxgate and search coil magnetometer concept using a racetrack core. *Geoscientific Instrumentation, Methods and Data Systems*, 7(4):265–276. (Cited on page 40.)
- Morgan, H. and Druckmüller, M. (2014). Multi-Scale Gaussian Normalization for Solar Image Processing. *Solar Physics*, 289(8):2945–2955. (Cited on page 169.)
- Mou, C., Madjarska, M. S., Galsgaard, K., and Xia, L. (2018). Eruptions from quiet Sun coronal bright points - I. Observations. *Astronomy & Astrophysics*, 619:A55. (Cited on pages 91, 92, 93 and 96.)
- Mozer, F. S., Bale, S. D., Bonnell, J. W., Drake, J. F., Hanson, E. L. M., and Mozer, M. C. (2021a). On the Origin of Switchbacks Observed in the Solar Wind. *The Astrophysical Journal*, 919(1):60. (Cited on page 26.)
- Mozer, F. S., Bonnell, J. W., Hanson, E. L. M., Gasque, L. C., and Vasko, I. Y. (2021b). Nonlinear Ion-acoustic Waves, Ion Holes, and Electron Holes in the Near-Sun Solar Wind. *The Astrophysical Journal*, 911(2):89. (Cited on page 80.)
- Müller, D., Cyr, O. C. S., Zouganelis, I., Gilbert, H. R., Marsden, R., Nieves-Chinchilla, T., Antonucci, E., Auchère, F., Berghmans, D., Horbury, T. S., Howard, R. A., Krucker, S., Maksimovic, M., Owen, C. J., Rochus, P., Rodriguez-Pacheco, J., Romoli, M., Solanki, S. K., Bruno, R., Carlsson, M., Fludra, A., Harra, L., Hassler, D. M., Livi, S., Louarn, P., Peter, H., Schühle, U., Teriaca, L., Iniesta, J. C. d. T.,

- Wimmer-Schweingruber, R. F., Marsch, E., Velli, M., Groof, A. D., Walsh, A., and Williams, D. (2020). The Solar Orbiter mission - Science overview. *Astronomy & Astrophysics*, 642:A1. (Cited on page 143.)
- Neugebauer, M. (2006). Comment on the abundances of rotational and tangential discontinuities in the solar wind. *Journal of Geophysical Research: Space Physics*, 111(A4). (Cited on page 78.)
- Neugebauer, M. (2012). Evidence for Polar X-Ray jets as sources of Microstream Peaks in the Solar Wind. *The Astrophysical Journal*, 750(1):50. (Cited on page 140.)
- Neugebauer, M., Clay, D. R., Goldstein, B. E., Tsurutani, B. T., and Zwickl, R. D. (1984). A reexamination of rotational and tangential discontinuities in the solar wind. *Journal of Geophysical Research: Space Physics*, 89(A7):5395–5408. (Cited on pages 65, 66 and 68.)
- Neugebauer, M. and Snyder, C. W. (1966). Mariner 2 observations of the solar wind: 1. Average properties. *Journal of Geophysical Research (1896-1977)*, 71(19):4469–4484. (Cited on page 6.)
- Nisticò, G., Bothmer, V., Patsourakos, S., and Zimbardo, G. (2009). Characteristics of EUV Coronal Jets Observed with STEREO/SECCHI. *Solar Physics*, 259(1-2):87–108. (Cited on pages 94 and 139.)
- Nolte, J. T. and Roelof, E. C. (1973). Large-Scale Structure of the Interplanetary Medium, I: High Coronal Source Longitude of the Quiet-Time Solar Wind. *Solar Physics*, 33:241–257. (Cited on pages 100 and 102.)
- Nóbrega-Siverio, D., Moreno-Insertis, F., Galsgaard, K., Krikova, K., Rouppe Van Der Voort, L., Joshi, R., and Madjarska, M. S. (2023). Deciphering Solar Coronal Heating: Energizing Small-scale Loops through Surface Convection. *The Astrophysical Journal Letters*, 958(2):L38. (Cited on pages 92 and 139.)
- Ofman, L. (2010). Wave Modeling of the Solar Wind. *Living Reviews in Solar Physics*, 7:4. (Cited on page 16.)
- Owens, M. J. and Forsyth, R. J. (2013). The Heliospheric Magnetic Field. *Living Reviews in Solar Physics*, 10(1):5. (Cited on pages 21 and 22.)
- Pan, H., Gou, T., and Liu, R. (2022). Sigmoid Formation through Slippage of a Single J-shaped Coronal Loop. *The Astrophysical Journal*, 937(2):77. (Cited on page 105.)
- Panasenco, O., Velli, M., D’Amicis, R., Shi, C., Réville, V., Bale, S. D., Badman, S. T., Kasper, J., Korreck, K., Bonnell, J. W., Wit, T. D. D., Goetz, K., Harvey, P. R., MacDowall, R. J., Malaspina, D. M., Pulupa, M., Case, A. W., Larson, D., Livi, R., Stevens, M., and Whittlesey, P. (2020). Exploring Solar Wind Origins and Connecting Plasma Flows from the *Parker Solar Probe* to 1 au: Nonspherical Source

- Surface and Alfvénic Fluctuations. *The Astrophysical Journal Supplement Series*, 246(2):54. (Cited on pages 103, 111 and 123.)
- Panesar, N. K., Tiwari, S. K., Berghmans, D., Cheung, M. C. M., Muller, D., Auchere, F., and Zhukov, A. (2021). The Magnetic Origin of Solar Campfires. *The Astrophysical Journal Letters*, 921(1):L20. (Cited on page 89.)
- Paraschiv, A. R., Bemporad, A., and Sterling, A. C. (2015). Physical properties of solar polar jets: A statistical study with Hinode XRT data. *Astronomy & Astrophysics*, 579:A96. (Cited on page 87.)
- Paraschiv, A. R., Dragomirescu, D., Stan, L., Talpeanu, D. C., Ivan, C., Radu, S., Lacatus, D. A., and Mierla, M. (2012). Coronal jet contribution to the slow Solar wind flux: preliminary results. *Advances in Astronomy and Space Physics*, 2:161–163. (Cited on pages 87 and 161.)
- Paraschiv, A. R., Lacatus, D. A., Badescu, T., Lupu, M. G., Simon, S., Sandu, S. G., Mierla, M., and Rusu, M. V. (2010). Study of Coronal Jets During Solar Minimum Based on STEREO/SECCHI Observations. *Solar Physics*, 264(2):365–375. (Cited on pages 93, 94 and 139.)
- Parker, E. N. (1958). Dynamics of the Interplanetary Gas and Magnetic Fields. *The Astrophysical Journal*, 128:664. (Cited on pages 6, 15, 16, 22 and 120.)
- Parker, E. N. (1972). Topological Dissipation and the Small-Scale Fields in Turbulent Gases. *The Astrophysical Journal*, 174:499. (Cited on page 5.)
- Patsourakos, S., Pariat, E., Vourlidas, A., Antiochos, S. K., and Wuelser, J. P. (2008). STEREO SECCHI Stereoscopic Observations Constraining the Initiation of Polar Coronal Jets. *The Astrophysical Journal*, 680(1):L73–L76. (Cited on pages 93 and 94.)
- Pearson, K. (1901). LIII. On lines and planes of closest fit to systems of points in space. *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, 2(11):559–572. (Cited on page 56.)
- Pecora, F., Matthaeus, W. H., Primavera, L., Greco, A., Chhiber, R., Bandyopadhyay, R., and Servidio, S. (2022). Magnetic Switchback Occurrence Rates in the Inner Heliosphere: Parker Solar Probe and 1 au. *The Astrophysical Journal Letters*, 929(1):L10. (Cited on page 28.)
- Peery, S., Liu, Y.-H., and Li, X. (2024). Conditions for Relativistic Magnetic Reconnection under the Presence of Shear Flow and Guide Field. *The Astrophysical Journal*, 964(2):144. (Cited on page 80.)
- Pellegrin-Frachon, T., Masson, S., Pariat, , Wyper, P. F., and DeVore, C. R. (2023). Interchange reconnection dynamics in a solar coronal pseudo-streamer. *Astronomy & Astrophysics*, 675:A55. (Cited on page 14.)

- Perri, B., Finley, A., Réville, V., Parenti, S., Brun, A. S., Strugarek, A., and Buchlin, (2024). Impact of far-side structures observed by Solar Orbiter on coronal and heliospheric wind simulations. *Astronomy & Astrophysics*, 687:A10. (Cited on page 108.)
- Perri, B., Leitner, P., Brchnelova, M., Baratashvili, T., Kuźma, B., Zhang, F., Lani, A., and Poedts, S. (2022). COCONUT, a Novel Fast-converging MHD Model for Solar Corona Simulations: I. Benchmarking and Optimization of Polytropic Solutions. *The Astrophysical Journal*, 936(1):19. (Cited on page 142.)
- Perrone, D., D’Amicis, R., De Marco, R., Matteini, L., Stansby, D., Bruno, R., and Horbury, T. S. (2020). Highly Alfvénic slow solar wind at 0.3 au during a solar minimum: Helios insights for Parker Solar Probe and Solar Orbiter. *Astronomy & Astrophysics*, 633:A166. (Cited on page 8.)
- Pesnell, W. D., Thompson, B. J., and Chamberlin, P. C. (2012). The Solar Dynamics Observatory (SDO). *Solar Physics*, 275(1-2):3–15. (Cited on page 96.)
- Poirier, N., Rouillard, A. P., Kouloumvakos, A., Przybylak, A., Fargette, N., Pobeda, R., Réville, V., Pinto, R. F., Indurain, M., and Alexandre, M. (2021). Exploiting White-Light Observations to Improve Estimates of Magnetic Connectivity. *Frontiers in Astronomy and Space Sciences*, 8. (Cited on page 145.)
- Poletto, G. and Suess, S. T., editors (2004). *The Sun and the Heliosphere as an Integrated System*, volume 317 of *Astrophysics and Space Science Library*. Springer Netherlands, Dordrecht. (Cited on page 92.)
- Pomoell, J. and Poedts, S. (2018). EUHFORIA: European heliospheric forecasting information asset. *Journal of Space Weather and Space Climate*, 8:A35. (Cited on page 142.)
- Pontieu, B., McIntosh, S., Carlsson, M., Hansteen, V., Tarbell, T., Boerner, P., Martinez-Sykora, J., Schrijver, C., and Title, A. (2011). The Origins of Hot Plasma in the Solar Corona. *Science (New York, N.Y.)*, 331:55–8. (Cited on page 89.)
- Priest, E. R. (1982). *Solar Magnetohydrodynamics*. Springer Netherlands, Dordrecht. (Cited on page 8.)
- Priest, E. R., Parnell, C. E., and Martin, S. F. (1994). A Converging Flux Model of an X-Ray Bright Point and an Associated Canceling Magnetic Feature. *The Astrophysical Journal*, 427:459. (Cited on page 92.)
- Raouafi, N. E., Patsourakos, S., Pariat, E., Young, P. R., Sterling, A. C., Savcheva, A., Shimojo, M., Moreno-Insertis, F., DeVore, C. R., Archontis, V., Török, T., Mason, H., Curdt, W., Meyer, K., Dalmasse, K., and Matsui, Y. (2016). Solar Coronal Jets: Observations, Theory, and Modeling. *Space Science Reviews*, 201(1):1–53. (Cited on pages 11, 14, 16, 87, 89, 90, 94, 161 and 162.)

- Raouafi, N. E., Petrie, G. J. D., Norton, A. A., Henney, C. J., and Solanki, S. K. (2008). Evidence for Polar Jets as Precursors of Polar Plume Formation. *The Astrophysical Journal*, 682:L137. (Cited on page 89.)
- Raouafi, N. E., Stenborg, G., Seaton, D. B., Wang, H., Wang, J., DeForest, C. E., Bale, S. D., Drake, J. F., Uritsky, V. M., Karpen, J. T., DeVore, C. R., Sterling, A. C., Horbury, T. S., Harra, L. K., Bourouaine, S., Kasper, J. C., Kumar, P., Phan, T. D., and Velli, M. (2023). Magnetic Reconnection as the Driver of the Solar Wind. *The Astrophysical Journal*, 945(1):28. (Cited on pages 89, 133 and 171.)
- Rasca, A. P., Farrell, W. M., Gruesbeck, J. R., MacDowall, R. J., Bale, S. D., and Kasper, J. C. (2023). Switchbacks and Associated Magnetic Holes Observed near the Alfvén Critical Surface. *The Astrophysical Journal*, 959(1):10. (Cited on page 140.)
- Riley, P., Linker, J. A., Mikić, Z., Lionello, R., Ledvina, S. A., and Luhmann, J. G. (2006). A Comparison between Global Solar Magnetohydrodynamic and Potential Field Source Surface Model Results. *The Astrophysical Journal*, 653:1510–1516. (Cited on page 142.)
- Rincon, F. and Rieutord, M. (2018). The Sun’s supergranulation. *Living Reviews in Solar Physics*, 15(1):6. (Cited on pages 26 and 88.)
- Rivera, Y. J., Badman, S. T., Stevens, M. L., Raines, J. M., Owen, C. J., Paulson, K., Niembro, T., Livi, S. A., Lepri, S. T., Landi, E., Halekas, J. S., Ervin, T., Dewey, R. M., Coburn, J. T., Bale, S. D., and Alterman, B. L. (2024a). Mixed Source Region Signatures inside Magnetic Switchback Patches Inferred by Heavy Ion Diagnostics. *The Astrophysical Journal*, 974(2):198. (Cited on pages 143 and 151.)
- Rivera, Y. J., Badman, S. T., Stevens, M. L., Verniero, J. L., Stawarz, J. E., Shi, C., Raines, J. M., Paulson, K. W., Owen, C. J., Niembro, T., Louarn, P., Livi, S. A., Lepri, S. T., Kasper, J. C., Horbury, T. S., Halekas, J. S., Dewey, R. M., De Marco, R., and Bale, S. D. (2024b). In situ observations of large-amplitude Alfvén waves heating and accelerating the solar wind. *Science*, 385(6712):962–966. (Cited on pages 30 and 143.)
- Roberts, M. A., Uritsky, V. M., DeVore, C. R., and Karpen, J. T. (2018). Simulated Encounters of the Parker Solar Probe with a Coronal-hole Jet. *The Astrophysical Journal*, 866(1):14. (Cited on pages 94 and 153.)
- Rosa Oliveira, R. A., da Silva Oliveira, M. W., Ojeda-González, A., and De La Luz, V. (2020). New Metric for Minimum Variance Analysis Validation in the Study of Interplanetary Magnetic Clouds. *Solar Physics*, 295(3):45. (Cited on page 50.)
- Rouillard, A. P., Pinto, R. F., Vourlidas, A., De Groof, A., Thompson, W. T., Bemporad, A., Dolei, S., Indurain, M., Buchlin, E., Sasso, C., Spadaro, D., Dalmasse, K., Hirzberger, J., Zouganelis, I., Strugarek, A., Brun, A. S., Alexandre, M., Berghmans,

- D., Raouafi, N. E., Wiegmann, T., Pagano, P., Arge, C. N., Nieves-Chinchilla, T., Lavarra, M., Poirier, N., Amari, T., Aran, A., Andretta, V., Antonucci, E., Anastasiadis, A., Auchère, F., Bellot Rubio, L., Nicula, B., Bonnín, X., Bouchemit, M., Budnik, E., Caminade, S., Cecconi, B., Carlyle, J., Cernuda, I., Davila, J. M., Etesi, L., Espinosa Lara, F., Fedorov, A., Fineschi, S., Fludra, A., Génot, V., Georgoulis, M. K., Gilbert, H. R., Giunta, A., Gomez-Herrero, R., Guest, S., Haberreiter, M., Hassler, D., Henney, C. J., Howard, R. A., Horbury, T. S., Janvier, M., Jones, S. I., Kozarev, K., Kraaikamp, E., Kouloumvakos, A., Krucker, S., Lagg, A., Linker, J., Lavraud, B., Louarn, P., Maksimovic, M., Maloney, S., Mann, G., Masson, A., Müller, D., Önel, H., Osuna, P., Orozco Suarez, D., Owen, C. J., Papaioannou, A., Pérez-Suárez, D., Rodríguez-Pacheco, J., Parenti, S., Pariat, E., Peter, H., Plunkett, S., Pomoell, J., Raines, J. M., Riethmüller, T. L., Rich, N., Rodríguez, L., Romoli, M., Sanchez, L., Solanki, S. K., St Cyr, O. C., Straus, T., Susino, R., Teriaca, L., Del Toro Iniesta, J. C., Ventura, R., Verbeeck, C., Vilmer, N., Warmuth, A., Walsh, A. P., Watson, C., Williams, D., Wu, Y., and Zhukov, A. N. (2020). Models and data analysis tools for the Solar Orbiter mission. *Astronomy & Astrophysics*, 642:A2. (Cited on page 99.)
- Ruffolo, D., Matthaeus, W. H., Chhiber, R., Usmanov, A. V., Yang, Y., Bandyopadhyay, R., Parashar, T. N., Goldstein, M. L., DeForest, C. E., Wan, M., Chasapis, A., Maruca, B. A., Velli, M., and Kasper, J. C. (2020). Shear-driven Transition to Isotropically Turbulent Solar Wind Outside the Alfvén Critical Zone. *The Astrophysical Journal*, 902(2):94. (Cited on page 29.)
- Santos, J. C., Büchner, J., Madjarska, M. S., and Alves, M. V. (2008). On the relation between DC current locations and an EUV bright point: A case study. *Astronomy & Astrophysics*, 490(1):345–352. (Cited on page 92.)
- Scherrer, P. H., Schou, J., Bush, R. I., Kosovichev, A. G., Bogart, R. S., Hoeksema, J. T., Liu, Y., Duvall, T. L., Zhao, J., Title, A. M., Schrijver, C. J., Tarbell, T. D., and Tomczyk, S. (2012). The Helioseismic and Magnetic Imager (HMI) Investigation for the Solar Dynamics Observatory (SDO). *Solar Physics*, 275:207–227. (Cited on page 107.)
- Schrijver, C. J. and DeRosa, M. L. (2003). Photospheric and heliospheric magnetic fields. *Solar Physics*, 212(1):165–200. (Cited on page 108.)
- Schrijver, C. J., Title, A. M., Ballegoijen, A. A. v., Hagenaar, H. J., and Shine, R. A. (1997). Sustaining the Quiet Photospheric Network: The Balance of Flux Emergence, Fragmentation, Merging, and Cancellation. *The Astrophysical Journal*, 487(1):424. (Cited on page 109.)
- Schwadron, N. A. and McComas, D. J. (2021). Switchbacks Explained: Super-Parker Fields—The Other Side of the Sub-Parker Spiral. *The Astrophysical Journal*, 909(1):95. (Cited on page 29.)

- Scudder, J. D. (2005). Geometry of magnetosonic shocks and plane-polarized waves: Coplanarity Variance Analysis (CVA). *Journal of Geophysical Research (Space Physics)*, 110:A02202. (Cited on page 150.)
- Seaton, D. B., Berghmans, D., Nicula, B., Halain, J.-P., De Groof, A., Thibert, T., Bloomfield, D. S., Raftery, C. L., Gallagher, P. T., Auchère, F., Defise, J.-M., D’Huys, E., Lecat, J.-H., Mazy, E., Rochus, P., Rossi, L., Schühle, U., Slemzin, V., Yalim, M. S., and Zender, J. (2013). The SWAP EUV Imaging Telescope Part I: Instrument Overview and Pre-Flight Testing. *Solar Physics*, 286(1):43–65. (Cited on page 167.)
- Shi, C., Panasenco, O., Velli, M., Tenerani, A., Verniero, J. L., Sioulas, N., Huang, Z., Brosius, A., Bale, S. D., Klein, K., Kasper, J., Wit, T. D. d., Goetz, K., Harvey, P. R., MacDowall, R. J., Malaspina, D. M., Pulupa, M., Larson, D., Livi, R., Case, A., and Stevens, M. (2022). Patches of Magnetic Switchbacks and Their Origins. *The Astrophysical Journal*, 934(2):152. (Cited on pages 26, 99, 125, 137 and 150.)
- Shibata, K. (1998). Evidence of Magnetic Reconnection in Solar Flares and a Unified Model of Flares. *Astrophysics and Space Science*, 264(1):129–144. (Cited on page 90.)
- Shibata, K., Ishido, Y., Acton, L. W., Strong, K. T., Hirayama, T., Uchida, Y., McAllister, A. H., Matsumoto, R., Tsuneta, S., Shimizu, T., Hara, H., Sakurai, T., Ichimoto, K., Nishino, Y., and Ogawara, Y. (1992). Observations of X-Ray Jets with the YOHKOH Soft X-Ray Telescope. *Publications of the Astronomical Society of Japan*, 44:L173–L179. (Cited on pages 11, 89, 93 and 162.)
- Smith, E. J. (1973). Identification of interplanetary tangential and rotational discontinuities. *Journal of Geophysical Research (1896-1977)*, 78(13):2054–2063. (Cited on pages 63 and 65.)
- Sonnerup, B. U. and Cahill Jr., L. J. (1967). Magnetopause structure and attitude from Explorer 12 observations. *Journal of Geophysical Research (1896-1977)*, 72(1):171–183. (Cited on pages 45, 46 and 49.)
- Sonnerup, B. U. and Scheible, M. (1998). Minimum and Maximum Variance Analysis. *ISSI Scientific Reports Series*, 1:185–220. (Cited on pages 49, 50, 54 and 55.)
- Squire, J., Chandran, B. D. G., and Meyrand, R. (2020). In-situ Switchback Formation in the Expanding Solar Wind. *The Astrophysical Journal*, 891(1):L2. (Cited on pages 29 and 150.)
- Stansby, D., Yeates, A., and Badman, S. T. (2020). pfsspy: A Python package for potential field source surface modelling. *Journal of Open Source Software*, 5(54):2732. (Cited on page 106.)
- Sterling, A. C. and Moore, R. L. (2020). Coronal-jet-producing Minifilament Eruptions as a Possible Source of Parker Solar Probe Switchbacks. *The Astrophysical Journal Letters*, 896(2):L18. (Cited on page 29.)

- Strong, K. T., Harvey, K., Hirayama, T., Nitta, N., Shimizu, T., and Tsuneta, S. (1992). Observations of the Variability of Coronal Bright Points by the Soft X-Ray Telescope on YOHKOH. *Publications of the Astronomical Society of Japan*, 44:L161–L166. (Cited on page 94.)
- Subramanian, S., Madjarska, M. S., and Doyle, J. G. (2010). Coronal hole boundaries evolution at small scales. II. XRT view. Can small-scale outflows at CHBs be a source of the slow solar wind. *Astronomy and Astrophysics*, 516:A50. (Cited on pages 117 and 119.)
- Suen, G. H. H., Owen, C. J., Verscharen, D., Horbury, T. S., Louarn, P., and Marco, R. D. (2023). Magnetic reconnection as an erosion mechanism for magnetic switchbacks. *Astronomy & Astrophysics*, 675:A128. (Cited on pages 31 and 79.)
- Tadesse, T., Wiegmann, T., MacNeice, P. J., Inhester, B., Olson, K., and Pevtsov, A. (2014). A Comparison Between Nonlinear Force-Free Field and Potential Field Models Using Full-Disk SDO/HMI Magnetogram. *Solar Physics*, 289(3):831–845. (Cited on page 142.)
- Tenerani, A., Sioulas, N., Matteini, L., Shi, C., and Velli, M. (2021). Evolution of Switchbacks in the Inner Heliosphere. *The Astrophysical Journal Letters*, 919(2):L31. (Cited on pages 28, 31 and 151.)
- Tenerani, A. and Velli, M. (2018). Nonlinear Firehose Relaxation and Constant-B Field Fluctuations. *The Astrophysical Journal*, 867:L26. (Cited on page 29.)
- Tenerani, A., Velli, M., and DeForest, C. (2016). Inward Motions in the Outer Solar Corona between 7 and 12 R: Evidence for Waves or Magnetic Reconnection Jets? *The Astrophysical Journal Letters*, 825(1):L3. (Cited on page 15.)
- Tenerani, A., Velli, M., Matteini, L., Réville, V., Shi, C., Bale, S. D., Kasper, J. C., Bonnell, J. W., Case, A. W., De Wit, T. D., Goetz, K., Harvey, P. R., Klein, K. G., Korreck, K., Larson, D., Livi, R., MacDowall, R. J., Malaspina, D. M., Pulupa, M., Stevens, M., and Whittlesey, P. (2020). Magnetic Field Kinks and Folds in the Solar Wind. *The Astrophysical Journal Supplement Series*, 246(2):32. (Cited on pages 86 and 161.)
- Tian, H., DeLuca, E. E., Cranmer, S. R., De Pontieu, B., Peter, H., Martínez-Sykora, J., Golub, L., McKillop, S., Reeves, K. K., Miralles, M. P., McCauley, P., Saar, S., Testa, P., Weber, M., Murphy, N., Lemen, J., Title, A., Boerner, P., Hurlburt, N., Tarbell, T. D., Wuelser, J. P., Kleint, L., Kankelborg, C., Jaeggli, S., Carlsson, M., Hansteen, V., and McIntosh, S. W. (2014). Prevalence of small-scale jets from the networks of the solar transition region and chromosphere. *Science*, 346(6207):1255711. (Cited on page 89.)

- Titov, V. S., Mikic, Z., Török, T., Linker, J. A., and Panasenco, O. (2012). 2010 August 1-2 Sympathetic Eruptions. I. Magnetic Topology of the Source-surface Background Field. *The Astrophysical Journal*, 759:70. (Cited on page 14.)
- Toth, G., Velli, M., and Holst, B. v. d. (2023). Theory of Magnetic Switchbacks Fully Supported by Parker Solar Probe Observations. *The Astrophysical Journal*, 957(2):95. (Cited on page 29.)
- Touresse, J., Pariat, E., and Froment, C. (2024). (in prep). *Accepted in Astronomy & Astrophysics*. (Cited on pages 94, 153 and 154.)
- Tsurutani, B. T. and Ho, C. M. (1999). A review of discontinuities and Alfvén waves in interplanetary space: Ulysses results. *Reviews of Geophysics*, 37(4):517–541. (Cited on pages 48, 53 and 76.)
- Tsurutani, B. T., Ho, C. M., Arballo, J. K., Lakhina, G. S., Glassmeier, K.-H., and Neubauer, F. M. (1997). Nonlinear electromagnetic waves and spherical arc-polarized waves in space plasmas. *Plasma Physics and Controlled Fusion*, 39(5A):A237–A250. (Cited on pages 46, 47 and 76.)
- Tsurutani, B. T., Ho, C. M., Arballo, J. K., Smith, E. J., Goldstein, B. E., Neugebauer, M., Balogh, A., and Feldman, W. C. (1996). Interplanetary discontinuities and Alfvén waves at high heliographic latitudes: Ulysses. *Journal of Geophysical Research: Space Physics*, 101(A5):11027–11038. (Cited on page 65.)
- Tsurutani, B. T., Lakhina, G. S., Sen, A., Hellinger, P., Glassmeier, K.-H., and Mannucci, A. J. (2018). A Review of Alfvénic Turbulence in High-Speed Solar Wind Streams: Hints From Cometary Plasma Turbulence. *Journal of Geophysical Research: Space Physics*, 123(4):2458–2492. (Cited on pages 37, 47 and 76.)
- Tu, C.-Y., Zhou, C., Marsch, E., Zong, Q., Zhao, L., Wang, J., and Wilhelm, K. (2005). Solar Wind Origin in Coronal Funnels. *Science (New York, N.Y.)*, 308:519–23. (Cited on page 30.)
- Tziotziou, K., Scullion, E., Shelyag, S., Steiner, O., Khomenko, E., Tsiropoula, G., Canivete Cuissa, J. R., Wedemeyer, S., Kontogiannis, I., Yadav, N., Kitiashvili, I. N., Skirvin, S. J., Dakanalis, I., Kosovichev, A. G., and Fedun, V. (2023). Vortex Motions in the Solar Atmosphere. *Space Science Reviews*, 219(1):1. (Cited on page 89.)
- Tziotziou, K., Tsiropoula, G., Kontogiannis, I., Scullion, E., and Doyle, J. G. (2018). A persistent quiet-Sun small-scale tornado. I. Characteristics and dynamics. *Astronomy and Astrophysics*, 618:A51. (Cited on page 89.)
- Vaiana, G. S., Davis, J. M., Giacconi, R., Krieger, A. S., Silk, J. K., Timothy, A. F., and Zombeck, M. (1973). X-Ray Observations of Characteristic Structures and Time Variations from the Solar Corona: Preliminary Results from SKYLAB. *The Astrophysical Journal*, 185:L47. (Cited on pages 90 and 91.)

- Valori, G., Löschl, P., Stansby, D., Pariat, E., Hirzberger, J., and Chen, F. (2022). Disambiguation of Vector Magnetograms by Stereoscopic Observations from the Solar Orbiter (SO)/Polarimetric and Helioseismic Imager (PHI) and the Solar Dynamic Observatory (SDO)/Helioseismic and Magnetic Imager (HMI). *Solar Physics*, 297(1):12. (Cited on page 142.)
- van Driel-Gesztelyi, L. and Green, L. M. (2015). Evolution of Active Regions. *Living Reviews in Solar Physics*, 12(1):1. (Cited on page 92.)
- Viall, N. M. and Borovsky, J. E. (2020). Nine Outstanding Questions of Solar Wind Physics. *Journal of Geophysical Research: Space Physics*, 125(7). (Cited on pages 9, 14, 15 and 138.)
- Viall, N. M. and Klimchuk, J. A. (2012). Evidence for Widespread Cooling in an Active Region Observed with the SDO Atmospheric Imaging Assembly. *The Astrophysical Journal*, 753:35. (Cited on page 93.)
- Viall, N. M. and Vourlidas, A. (2015). Periodic Density Structures and the Origin of the Slow Solar Wind. *The Astrophysical Journal*, 807(2):176. (Cited on page 14.)
- Vinogradov, A., Alexandrova, O., Démoulin, P., Artemyev, A., Maksimovic, M., Mangeney, A., Vasiliev, A., Petrukovich, A. A., and Bale, S. (2024). Embedded Coherent Structures from Magnetohydrodynamics to Sub-ion Scales in Turbulent Solar Wind at 0.17 au. *The Astrophysical Journal*, 971(1):88. (Cited on page 150.)
- Vourlidas, A., Howard, R. A., Plunkett, S. P., Korendyke, C. M., Thernisien, A. F. R., Wang, D., Rich, N., Carter, M. T., Chua, D. H., Socker, D. G., Linton, M. G., Morrill, J. S., Lynch, S., Thurn, A., Van Dyne, P., Hagood, R., Clifford, G., Grey, P. J., Velli, M., Liewer, P. C., Hall, J. R., DeJong, E. M., Mikic, Z., Rochus, P., Mazy, E., Bothmer, V., and Rodmann, J. (2016). The Wide-Field Imager for Solar Probe Plus (WISPR). *Space Science Reviews*, 204:83–130. (Cited on page 17.)
- Walén, C. (1944). On the Theory of Sunspots. *Arkiv for Matematik, Astronomi och Fysik*, 30A:1–87. (Cited on page 36.)
- Wang, R., Vasko, I., Phan, T., and Mozer, F. (2024). Solar Wind Current Sheets: MVA Inaccuracy and Recommended Single-Spacecraft Methodology. *Journal of Geophysical Research: Space Physics*, 129. (Cited on page 150.)
- Wang, Y., Sheeley, Jr., N. R., Socker, D. G., Howard, R. A., Brueckner, G. E., Michels, D. J., Moses, D., St. Cyr, O. C., Llebaria, A., and Delaboudiniere, J. (1998). Observations of Correlated White-Light and Extreme-Ultraviolet Jets from Polar Coronal Holes. *The Astrophysical Journal*, 508(2):899–907. (Cited on pages 87, 89, 94, 139 and 161.)
- Wang, Y. M., Ko, Y. K., and Grappin, R. (2009). Slow Solar Wind from Open Regions with Strong Low-Coronal Heating. *The Astrophysical Journal*, 691:760–769. (Cited on page 14.)

- Wang, Y. M. and Sheeley, Jr., N. R. (1990). Solar Wind Speed and Coronal Flux-Tube Expansion. *The Astrophysical Journal*, 355:726. (Cited on page 14.)
- West, M. J., Seaton, D. B., D’Huys, E., Mierla, M., Laurenza, M., Meyer, K. A., Berghmans, D., Rachmeler, L. R., Rodriguez, L., and Stegen, K. (2022). A Review of the Extended EUV Corona Observed by the Sun Watcher with Active Pixels and Image Processing (SWAP) Instrument. *Solar Physics*, 297(10):136. (Cited on page 168.)
- West, M. J., Seaton, D. B., Wexler, D. B., Raymond, J. C., Del Zanna, G., Rivera, Y. J., Kobelski, A. R., Chen, B., DeForest, C., Golub, L., Caspi, A., Gilly, C. R., Kooi, J. E., Meyer, K. A., Alterman, B. L., Alzate, N., Andretta, V., Auchère, F., Banerjee, D., Berghmans, D., Chamberlin, P., Chitta, L. P., Downs, C., Giordano, S., Harra, L., Higginson, A., Howard, R. A., Kumar, P., Mason, E., Mason, J. P., Morton, R. J., Nykyri, K., Patel, R., Rachmeler, L., Reardon, K. P., Reeves, K. K., Savage, S., Thompson, B. J., Van Kooten, S. J., Viall, N. M., Vourlidis, A., and Zhukov, A. N. (2023). Defining the Middle Corona. *Solar Physics*, 298(6):78. (Cited on page 102.)
- Whittlesey, P. L., Larson, D. E., Kasper, J. C., Halekas, J., Abatcha, M., Abiad, R., Berthomier, M., Case, A. W., Chen, J., Curtis, D. W., Dalton, G., Klein, K. G., Korreck, K. E., Livi, R., Ludlam, M., Marckwordt, M., Rahmati, A., Robinson, M., Slagle, A., Stevens, M. L., Tiu, C., and Verniero, J. L. (2020). The Solar Probe ANalyzers—Electrons on the Parker Solar Probe. *The Astrophysical Journal Supplement Series*, 246(2):74. (Cited on pages 21 and 43.)
- Wiegmann, T. and Sakurai, T. (2021). Solar force-free magnetic fields. *Living Reviews in Solar Physics*, 18(1):1. (Cited on page 142.)
- Wiegmann, T., Thalmann, J. K., and Solanki, S. K. (2014). The magnetic field in the solar atmosphere. *The Astronomy and Astrophysics Review*, 22(1):78. (Cited on page 107.)
- Woolley, T., Matteini, L., Horbury, T. S., Bale, S. D., Woodham, L. D., Laker, R., Alterman, B. L., Bonnell, J. W., Case, A. W., Kasper, J. C., Klein, K. G., Martinić, M. M., and Stevens, M. (2020). Proton core behaviour inside magnetic field switchbacks. *Monthly Notices of the Royal Astronomical Society*, 498(4):5524–5531. (Cited on page 79.)
- Worden, J. and Harvey, J. (2000). An Evolving Synoptic Magnetic Flux map and Implications for the Distribution of Photospheric Magnetic Flux. *Solar Physics*, 195(2):247–268. (Cited on page 108.)
- Wyper, P. F., DeVore, C. R., Antiochos, S. K., Pontin, D. I., Higginson, A. K., Scott, R., Masson, S., and Pelegrin-Frachon, T. (2022). The Imprint of Intermittent Interchange Reconnection on the Solar Wind. *The Astrophysical Journal Letters*, 941(2):L29. (Cited on page 72.)

- Yamauchi, Y., Suess, S. T., Steinberg, J. T., and Sakurai, T. (2004). Differential velocity between solar wind protons and alpha particles in pressure balance structures. *Journal of Geophysical Research (Space Physics)*, 109:A03104. (Cited on pages 18 and 156.)
- Yardley, S. L., Brooks, D. H., D’Amicis, R., Owen, C. J., Long, D. M., Baker, D., Démoulin, P., Owens, M. J., Lockwood, M., Mihailescu, T., Coburn, J. T., Dewey, R. M., Müller, D., Suen, G. H. H., Ngampoopun, N., Louarn, P., Livi, S., Lepri, S., Fludra, A., Haberreiter, M., and Schühle, U. (2024). Multi-source connectivity as the driver of solar wind variability in the heliosphere. *Nature Astronomy*, 8(8):953–963. (Cited on page 143.)
- Young, P. R. (2015). Dark Jets in Solar Coronal Holes. *The Astrophysical Journal*, 801(2):124. (Cited on page 139.)
- Zank, G. P., Nakanotani, M., Zhao, L.-L., Adhikari, L., and Kasper, J. (2020). The Origin of Switchbacks in the Solar Corona: Linear Theory. *The Astrophysical Journal*, 903(1):1. (Cited on page 29.)
- Zhang, J., Kundu, M. R., and White, S. M. (2001). Spatial Distribution and Temporal Evolution of Coronal Bright Points. *Solar Physics*, 198(2):347–365. (Cited on page 90.)

Nina BIZIEN

Évolution et Sources des Switchbacks Observés dans le Vent Solaire

Résumé :

Les observations récentes de la sonde Parker Solar Probe (PSP), lancée en 2018, apportent des données inédites sur l'origine du vent solaire. L'objectif scientifique de la mission est de révéler les mécanismes physiques au plus proche du Soleil qui seraient reliés à deux questions fondamentales, le problème du chauffage et de l'accélération du vent solaire. La mission a révélé l'omniprésence de déflexions soudaines du champ magnétique du vent solaire, les « switchbacks ». Ces structures, qui se propagent à la vitesse d'Alfvén, pourraient être à la source de transferts d'énergie qui répondraient à ces questions. À ce jour, leur origine ainsi que leur capacité à survivre dans le vent solaire restent à élucider.

Je vais présenter le travail accompli durant cette thèse dans le but de comprendre l'origine et l'évolution des switchbacks à partir de mesures in situ du champ magnétique ainsi que de observations par télédétection. Dans un premier temps, je me concentre sur la nature des frontières des switchbacks, qui sont l'intervalle pendant lequel se produit la majeure partie de la déviation du champ magnétique. En raison de la complexité de la structure 3D de ces frontières, leur analyse nécessite la définition d'une nouvelle méthodologie. Je montre que leur nature correspond à des structures fermées. Ce nouveau résultat suggère que l'érosion des switchbacks est plus faible que prévu. Cela pourrait expliquer leur présence à de grandes distances du Soleil. Ce résultat est aussi compatible avec une origine des switchbacks dans la basse atmosphère du Soleil, ce qui motive la seconde partie de ma thèse, qui se concentre sur l'origine des switchbacks. Il existe plusieurs hypothèses non-exclusives quant à leur origine. Cependant, il y a actuellement un consensus sur le rôle joué par de petits événements de reconnexion dans la basse couronne du Soleil dans la création des conditions nécessaires à la génération des switchbacks. Cette hypothèse n'a pas encore été confirmée, en raison de la difficulté de connecter les événements transitoires dans la couronne aux structures se propageant dans le vent solaire. L'objectif de cette étude est d'établir, statistiquement et à partir d'observations, si des jets de points brillants coronaux localisés dans des trous coronaux peuvent être des précurseurs des switchbacks observés in situ par le satellite. Bien que cette étude soit la plus détaillée à ce jour, les résultats ne montrent pas de corrélation claire. Différentes raisons sont envisagées pour l'expliquer. Les modèles établis ne seraient pas suffisamment précis pour étudier les petits événements éruptifs ce qui nécessiterait une analyse plus fine de la configuration magnétique dans la basse couronne. Les résultats pourraient aussi être influencés par notre compréhension limitée des processus évolutifs qui se sont déroulés au cours de la propagation du vent solaire. L'étude d'un éventail plus large d'événements éruptifs et non limité aux jets pourrait aussi être nécessaire pour identifier les événements précurseurs des switchbacks.

Mots clés : Vent solaire, Couronne solaire, Parker Solar Probe, Switchbacks

Evolution and Sources of Switchbacks Observed in the Solar Wind

Abstract :

Recent observations by the Parker Solar Probe (PSP) mission, launched in 2018, provide new clues on the origin of the solar wind. The scientific goal of the mission is to reveal the physical mechanisms closest to the Sun that are linked to two fundamental and unresolved questions, the problem of heating and acceleration of the solar wind. The mission revealed the ubiquity of sudden deflections of the solar wind's magnetic field, known as switchbacks. These structures, which propagate at the Alfvén speed, could be the source of energy transfers that answer these questions. Their origin and their ability to survive in the solar wind have yet to be elucidated.

The work carried out in this thesis aims to understand the origin and evolution of switchbacks based on both in situ magnetic field measurements and remote sensing observations. First, I focus on the nature of switchback boundaries, the intervals that include most of the magnetic field deflection. Due to the complex 3D structure of these boundaries, their analysis requires the definition of a new methodology. I show that the nature of the boundaries corresponds to closed structures, which is a new result. This has an implication on the propagation of switchbacks, as the results suggest that their erosion may be much slower than expected. This, in turn, may explain why we observe switchbacks far from the Sun. The results are also compatible with an origin of switchbacks that is rooted in the lower solar atmosphere, which motivates the second part of my thesis. There are various non-exclusive hypotheses as to the origin of switchbacks, including an origin in the Sun's lower atmosphere. Nevertheless, there is currently a consensus on the role that small reconnection events play in the Sun's lower corona in creating conditions for generating switchbacks through magnetic reconnection. This hypothesis has yet to be verified due to the difficulty of relating transient events in the corona with structures propagating in the solar wind. The aim of this study is to establish, statistically and through observations, whether jets from coronal bright points located in coronal holes can be precursors of switchbacks. Although this study is the most detailed approach to date, the results show no clear correlation. Different reasons are considered. The implemented models would not be precise enough to study the small-scale eruptive events, that would require a finer analysis of the magnetic topology in the lower corona. Evolutionary changes during solar wind propagation could affect our findings. It could also mean that a wider range of eruptive events, not just jets, might be the precursors of switchbacks.

Keywords : Solar Wind, Solar Corona, Parker Solar Probe, Switchbacks



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