Ion Composition and Differential Flow in Switchback Patches Across the Inner Heliosphere

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Introduction

The young solar wind is permeated by large-amplitude, non-linear magnetic field deflections known as **switchbacks**, characterized by rapid rotations of the magnetic field vector while the magnetic field magnitude remains approximately conserved. First extensively observed by Parker Solar Probe (Bale et al., 2019) and later by Solar Orbiter, switchbacks are now recognized as a ubiquitous feature of the near-Sun heliosphere. They display self-similar structures over a broad range of timescales, down to ion gyro-periods (Dudok de Wit et al., 2020), and are frequently organized into extended **switchback patches**.

The origin of these structures remains debated. One leading mechanism is **interchange magnetic reconnection** in the low corona (Fisk Kasper, 2020), which may inject Alfvénic perturbations that subsequently evolve into switchbacks in the expanding solar wind (Gannouni et al., 2023; Touresse et al., 2024). Such processes could leave observable signatures in ion populations, particularly in the composition and thermodynamic properties of alpha particles.

Recent observations suggest that switchback patches may be associated with localized enhancements of **alpha particle abundance** (Bale et al., 2023), potentially reflecting distinct coronal source regions or plasma release processes. Investigating the plasma composition within and around switchback patches therefore provides an important constraint on their formation and propagation mechanisms.

Alpha Particle Abundance Modulation

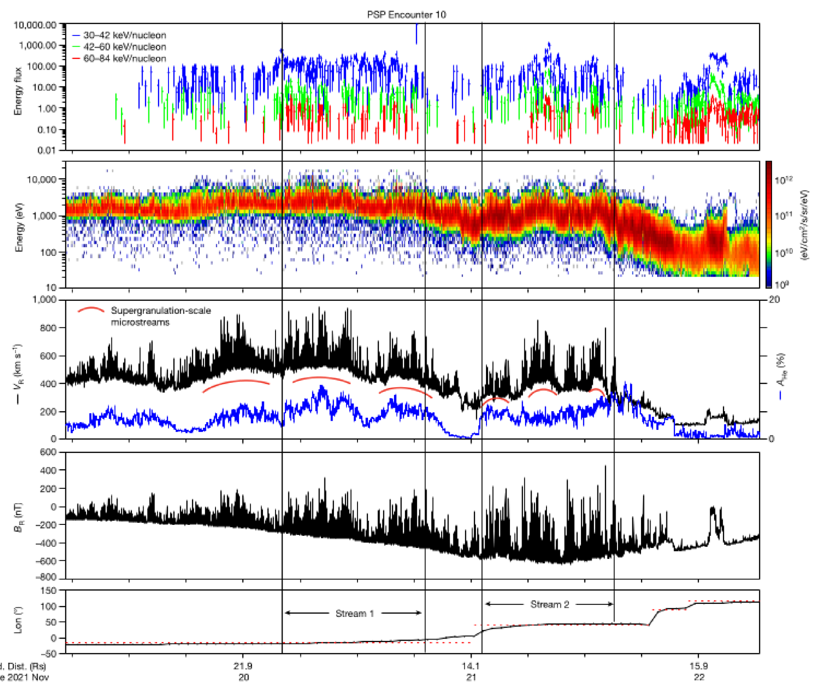


Figure 1. Time series measurements of the solar wind plasma and magnetic field through the November 2021 solar encounter. From Bale et al., 2023

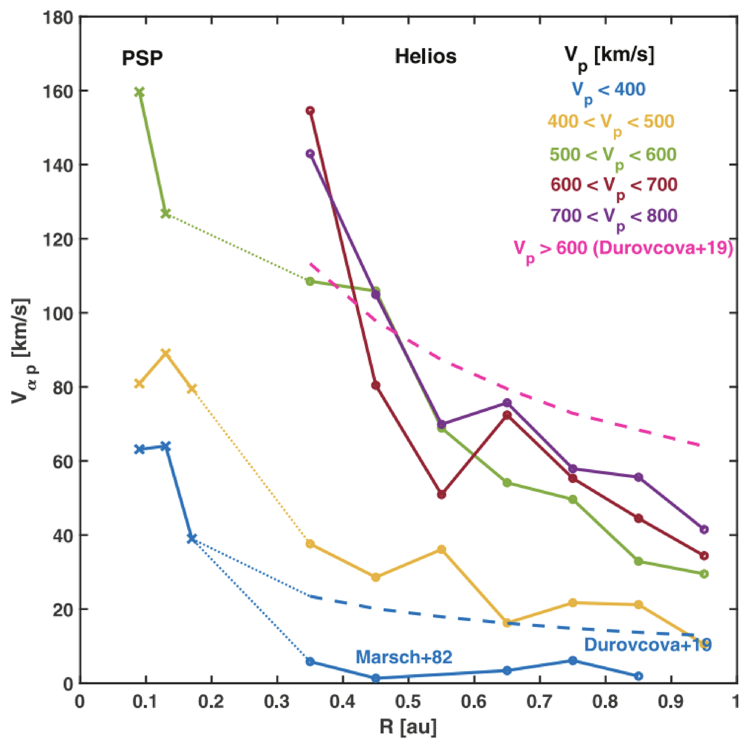


Figure 2. Averages of the alpha–proton differential flow of the Helios and PSP data sets as a function of distance from the Sun for different ranges of solar wind speeds. From Mostafavi et al., 2022

Parker Solar Probe observations showed that switchback patches associated with fast solar wind streams exhibit a positive correlation between alpha particle abundance and with increased solar wind velocity, suggesting a common coronal origin linked to interchange reconnection processes.

Measurements of the young solar wind also reveal that the alpha–proton differential flow progressively decreases with radial distance. Since alpha abundance and differential streaming are coupled through mass and momentum conservation, with $n_\alpha/n_p \propto V_p/V_\alpha$, radial variations of the differential flow may also be associated with changes in alpha particle abundance.

Analysis of the alpha abundance / velocity correlation in PSP and SolO data

We designed a methodology to assess the radial evolution of the correlation at the patches' scale (supergranulation)

I.Computing the normalized deflection

A switchback is defined as a deflection from the Parker spiral (method from Fargette et al., 2021:

Parker spiral angle

$$\psi_p(t) = \arctan\left(\frac{-\omega(r(t)-r_0)}{V_r(t)}\right) + k\pi$$

Field amplitude

$$\boldsymbol{B}_p(t) = |\boldsymbol{B}(t)| \begin{bmatrix} \cos\psi_p(t) \\ \sin\psi_p(t) \\ 0 \end{bmatrix}_{RTN}$$

Normalized deflection (Dudok de Wit et al., 2020)

$$z(t) = \frac{1}{2}[1-\cos(\alpha)] \quad \text{with} \quad \cos(\alpha(t)) = \frac{\boldsymbol{B}_p(t)\cdot\boldsymbol{B}(t)}{|\boldsymbol{B}(t)|^2}$$

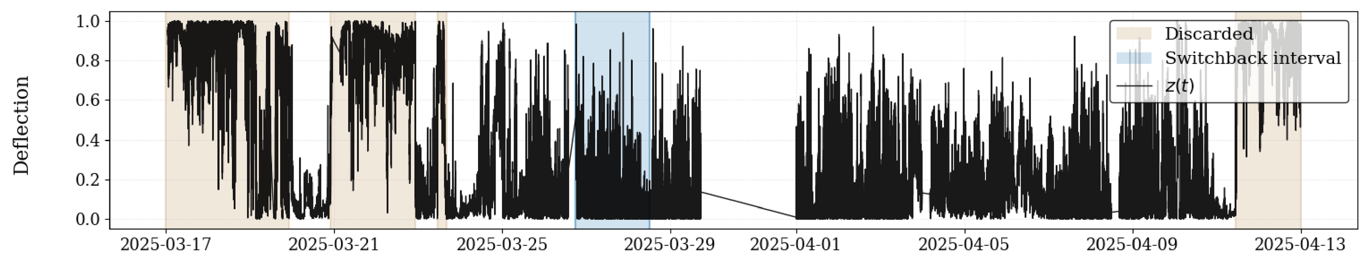


Figure 3. Normalized deflection computed for the 2025 Fast-wind SOOP interval. Some regions have been discarded for the detection algorithm due to polarity reversal to sunward magnetic field

First the normalized deflection is computed relative to the local Parker spiral direction, allowing us to isolate magnetic field rotations associated with switchbacks. In this representation, each peak corresponds to a switchback event, independently of the background solar wind orientation.

II. Filter high frequency signal with FFT

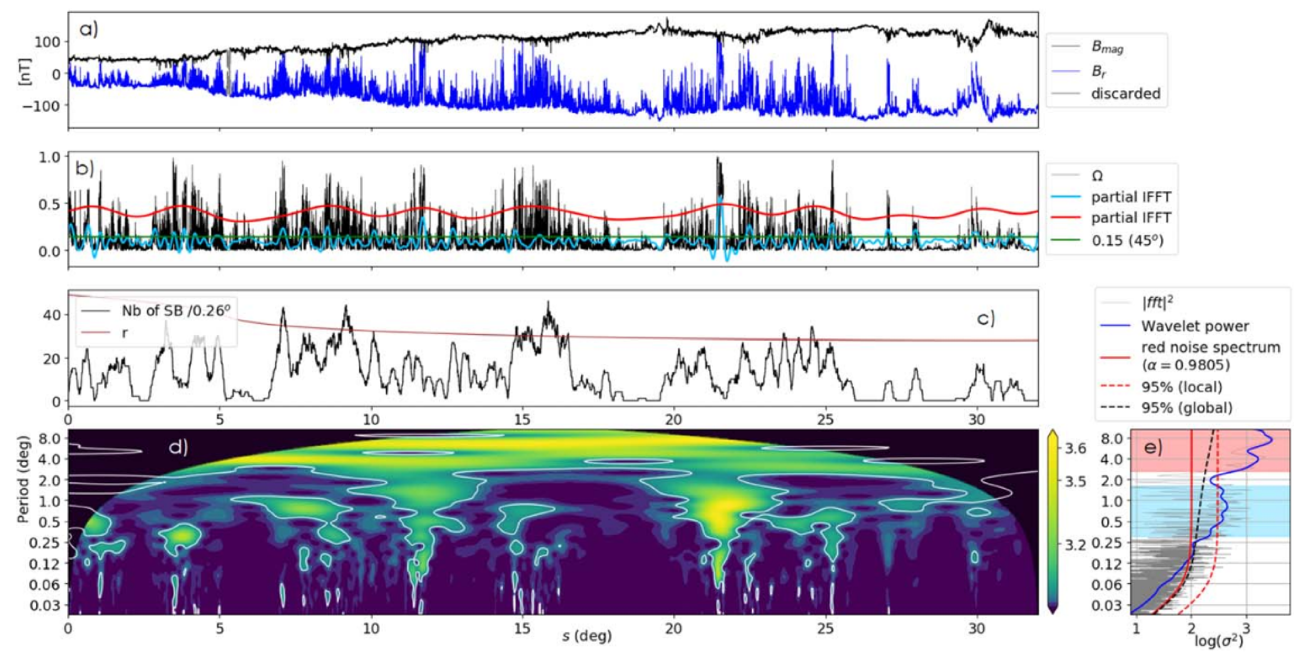


Figure 4. Spatial analysis for E5 (a) $||B||$ and B_R plotted as a function of the angular displacement s. From Fargette et al., 2021

Then the deflection signal is filtered using partial inverse Fourier transforms to separate large-scale structures from small-scale fluctuations. A wavelet transform is then applied to compute the time–scale distribution of magnetic power. Regions exhibiting enhanced power over a broad range of scales are identified as switchback patches (super-granules scales). This approach provides an automated and scale-sensitive method to detect coherent switchback activity.

Repeating this method on alpha particle abundance N_α/N_p will allow us to compute the correlation with the solar wind speed.

III. Study of the radial evolution of the correlation

We have identified use this methodology on a catalog of switchback patches identified across different radial distances.

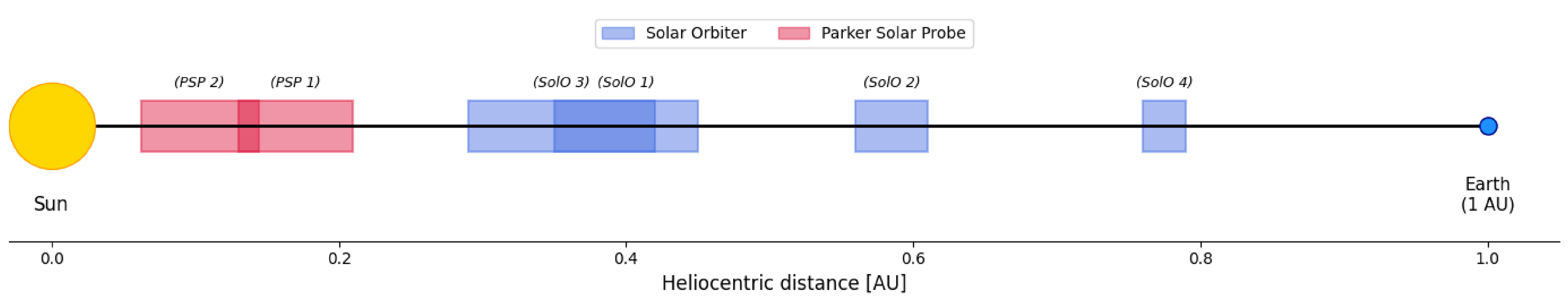


Figure 5. Representation of the radial distribution of the patches from our catalog from both Parker Solar Probe (in red) and Solar Orbiter (in blue)

Coloured intervals indicate the heliocentric distances where switchback patches have been identified and will be analyzed, providing a broad radial sampling of the young solar wind.

To complete this study with Solar Orbiter we need an accurate computation of protons and alpha moments

Proton Alpha Sensor (PAS) Data

Context

To accurately assess the alpha abundances, we need a robust method to separate alpha and proton populations in PAS data. Public **L2** data provide proton moments only (Fedorov et al., 2020). Existing **L3** proton/alpha moments (Ďurovcová & Přech, 2021), based on bi-Maxwellian fits in velocity space, can fail when proton and alpha populations overlap or when proton beams are present. To overcome these limitations, we developed a new machine-learning-based method to separate ion populations and compute reliable moments.

Method

The **particle distribution function** $f(E,\theta,\phi)$ is first integrated over the angular coordinates:

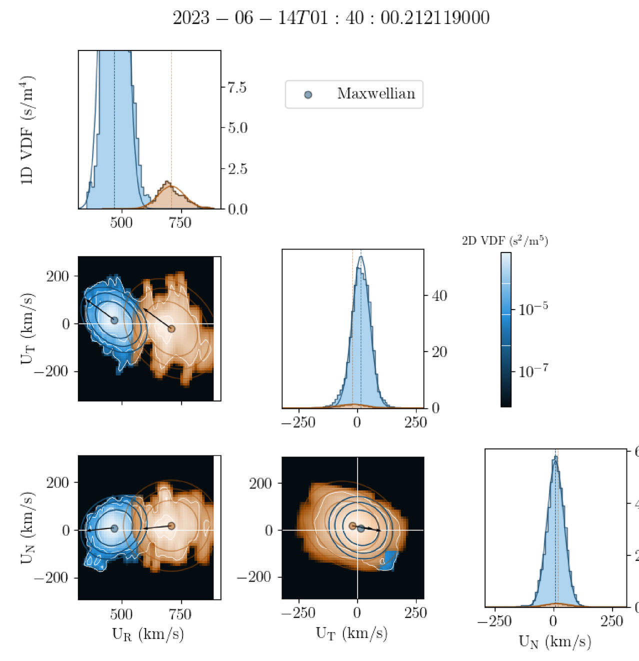
$$f_E(E) = \int_\Omega f(E,\theta,\phi)\, d\Omega$$

A **Gaussian Mixture Model (GMM)** is then fitted to $f_E(E)$ in energy space:

$$f(x;w,\sigma,\mu) = \sum_{i=1}^{N} \frac{w_i}{\sqrt{2\pi\sigma_i^2}} exp\left(\frac{-(x-\mu_i)^2}{2\sigma_i^2}\right)$$

w_i, μ_i and σ_i are the weight, centroid energy, and standard deviation of the i-th population. The GMM is then used to estimate the **probability associated with each population** and separate the original 3D distribution:

$$P_k(E) = \frac{f_k(E)}{\sum_{j=1}^{N} f_j(E)}\,; \qquad f_k(E,\theta,\phi) = P_k(E) f(E,\theta,\phi)$$



Comparison with previous alpha dataset

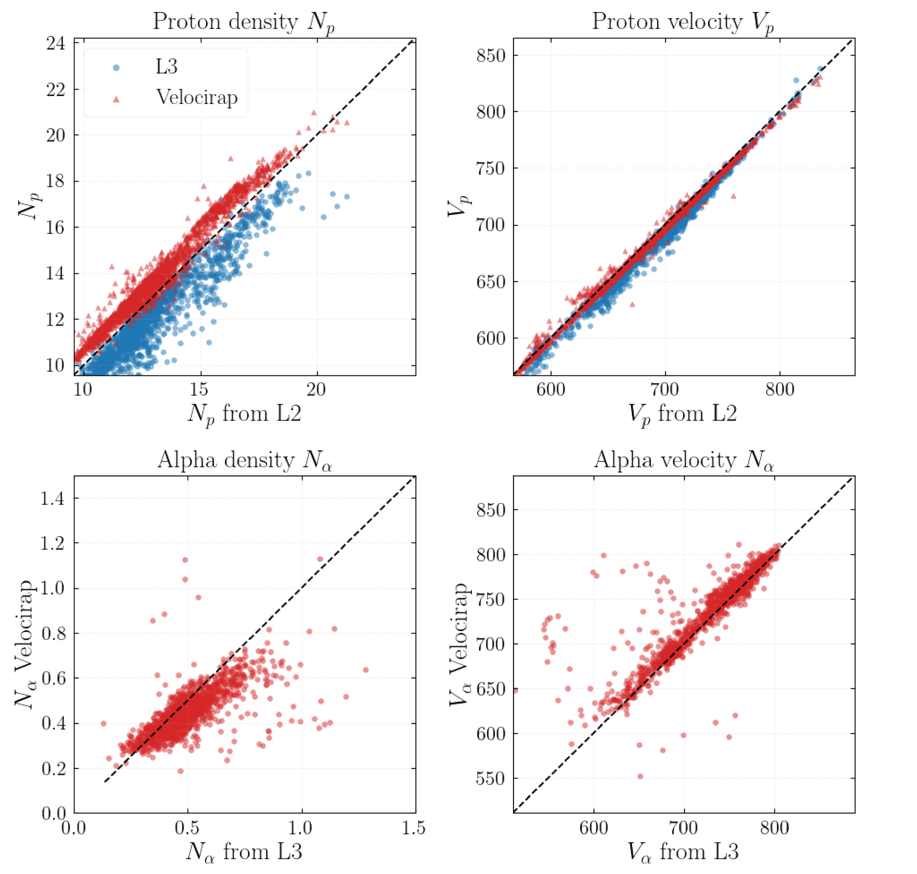


Figure 6. Comparison of proton and alpha moments from L2, L3 (in blue), and Velocirap (in red) datasets. The dashed line indicates the one-to-one relation. Proton moments show strong agreement between datasets, while alpha moments exhibit larger dispersion due to lower particle counts.

Since the public L2 dataset does not provide alpha moments, only Velocirap and L3 products are compared in the bottom panels.

Proton density and velocity show a **strong correlation** between the three datasets, indicating that Velocirap reliably reproduces the proton bulk properties.

The proton velocity agreement is particularly good and remains close to the one-to-one relation over the full range of observed values.

Alpha particle moments exhibit a **larger dispersion**, mainly due to the lower alpha counts and the difficulty of accurately separating the alpha population from the proton core in the velocity distribution functions.

Despite this increased scatter, Velocirap remains globally consistent with the L3 alpha moments and successfully captures the main alpha population trends.

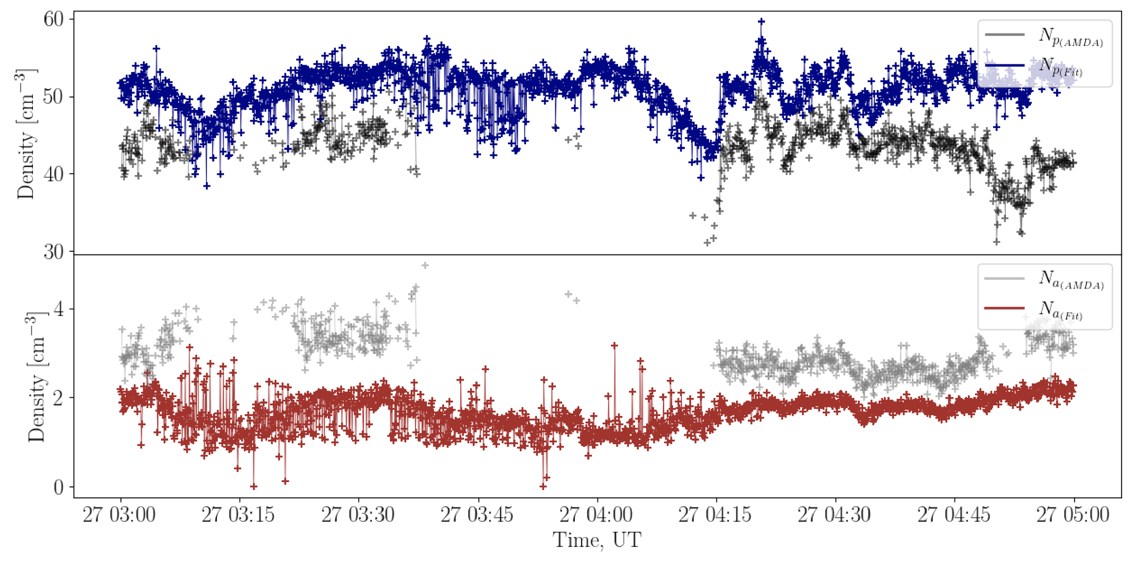


Figure 7. Comparison of proton (top panel) and alpha (bottom panel) densities between L3 data (in grey) and velocirap (in color). The main data gap is highlighted with the red shaded area.

One of the main advantages of our method is its robustness against overlapping ion populations, significantly reducing the risk of proton/alpha misidentification and improving the reliability of the derived plasma moments.

In this example, more than **43%** of the distribution functions did not return any moments with the standard approach because the algorithm was unable to correctly determine the separation between proton and alpha populations in energy phase space. Our method remains able to isolate both populations even in highly mixed distributions, enabling a more complete and physically consistent characterization of the plasma.

Velocirap Python Library

Velocirap is an open source python framework to handle and visualise Ion Distribution Functions for Solar Orbiter, Parker Solar Probe and Helioswarm.

For detailled information on this project go see Naïs Fargette's poster: **"Velocirap, a python library for advanced analysis of ion velocity distribution functions"**

github.com/Nfargette/velocirap_public

Perspectives

Velocirap Algorithm

Further improve the robustness of the algorithm in difficult and highly mixed cases, and develop a full 2D fitting approach to better resolve complex ion populations in (E,θ) phase space.

Radial analysis

Use our methods and newly derived ion moments to extend existing radial evolution studies of alpha abundance and differential streaming to *Solar Orbiter* observations.

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