

On Alfvénic turbulence of solar wind streams observed by Solar Orbiter during March 2022 perihelion and their source regions

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ABSTRACT

Context. It has been recently accepted that the standard classification of the solar wind solely according to flow speed is outdated, and particular interest has been devoted to the study of the origin and evolution of so-called Alfvénic slow solar wind streams and to what extent such streams resemble or differ from fast wind.

Aims. In March 2022, Solar Orbiter completed its first nominal phase perihelion passage. During this interval, it observed several Alfvénic streams, allowing for characterization of fluctuations in three slow wind intervals (AS1-AS3) and comparison with a fast wind stream (F) at almost the same heliocentric distance.

Methods. This work makes use of Solar Orbiter plasma parameters from the Solar Wind Analyzer (SWA) and magnetic field measurements from the magnetometer (MAG). The magnetic connectivity to the solar sources of selected solar wind intervals was reconstructed using a ballistic extrapolation based on measured solar wind speed down to the (spherical) source surface at $2.5R_{\odot}$, below which a potential field extrapolation was used to map back to the Sun. The source regions were identified using SDO/AIA observations. A spectral analysis of in situ measured magnetic field and velocity fluctuations was performed to characterize correlations, Alfvénicity, normalized cross-helicity, and residual energy in the frequency domain as well as intermittency of the fluctuations and spectral energy transfer rate estimated via mixed third-order moments. A machine learning technique was used to separate proton core, proton beam, and alpha particles and to study v - b correlations for the different ion populations in order to evaluate the role played by each population in determining the Alfvénic content of solar wind fluctuations.

Results. The comparison between fast wind and Alfvénic slow wind intervals highlights the differences between the two solar wind regimes: The fast wind is characterized by larger amplitude fluctuations, and magnetic and velocity fluctuations are closer to equipartition of energy. In fact the Alfvénic slow wind streams appear to be on a spectrum of wind types, with AS1, originating from open field lines neighboring active regions and displaying similarities with the fast wind in terms of fluctuation amplitude and turbulence characteristics, but not with respect to the alpha particles and proton beams. The other two slow streams differed both in their sources as well as plasma characteristics, with AS2 coming from the expansion of a narrow coronal hole corridor and AS3 from a region straddling a pseudostreamer. The latter displayed the coldest and highest density but the slowest stream with the smallest fluctuation amplitude and greatest magnetic energy excess. It also showed the largest scatter in proton beam speeds and the greatest difference in speed between proton beam and alpha particles.

Conclusions. This study shows how the old fast–slow solar wind dichotomy, already called into question by the observations of slower Alfvénic solar wind streams, should further be refined, as the Alfvénic slow wind, originating in different solar wind regions, show significant differences in density, temperature, and proton and alpha-particle properties in the inner heliosphere. The observations presented here provide the starting point for a better understanding of the origin and evolution of different solar wind streams as well as the evolving turbulence contained within.

Key words. magnetohydrodynamics (MHD) – plasmas – turbulence – methods: data analysis – space vehicles: instruments – solar wind

1. Introduction

The solar wind data collected by the Helios mission over a period spanning from solar minimum in 1976 to solar maximum in the early 1980s have shown several differences between fast and slow solar wind streams. These point to a slow wind characterized by a lower proton temperature and higher density, and in general much more variable properties with respect to fast wind. Moreover, the freezing-in temperature is anticorrelated with the wind speed, and the thermodynamics of electrons, protons, and heavy ions has been observed to vary with speed (e.g. Marsch et al. 1982a,b; Lopez & Freeman 1986; Geiss et al. 1995; Neugebauer et al. 1996; Zurbuchen et al. 1999; von Steiger et al. 2000; Matthaeus et al. 2006; Hellinger et al. 2006;

Schwenn 2006; Kasper et al. 2008, 2012; Maruca et al. 2012, 2013; Matteini et al. 2013; Abbo et al. 2016; Stansby et al. 2019).

To further characterize different solar wind regimes, the very first observations by Mariner 5 highlighted the presence of Alfvénic fluctuations in the solar wind identified as nearly incompressible (i.e., almost constant number density and magnetic field magnitude) fluctuations accompanied by large correlations between velocity and magnetic field components (Belcher et al. 1969; Belcher & Davis 1971; Belcher & Solodina 1975), as predicted by the magnetohydrodynamics (MHD) theory for linear waves. Alfvénic fluctuations are thought to play a major role in regulating wave-particle interactions and ultimately determine the presence of anisotropies and beams in ion velocity distribution functions (VDFs) and ion

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drift. These are very common features in the solar wind, especially in the main portion of fast wind streams, and are a fundamental element in different heliospheric processes, such as solar wind heating and acceleration, energetic particle acceleration, and cosmic ray propagation.

In general, proton VDFs in fast streams are characterized by large anisotropy with $T_{\perp} > T_{\parallel}$ and by the presence of a secondary beam population, while the typical slow wind VDFs are nearly isotropic and show no relevant beams (Marsch et al. 1982b; Hellinger et al. 2006; Matteini et al. 2013). Early observations by Feldman et al. (1973) and more detailed analysis of the proton beam with Helios in the high-speed solar wind (Marsch et al. 1982b) and Ulysses in the high-latitude solar wind (Goldstein et al. 2000) have shown a beam drift velocity relative to the core part, V_D , larger than the Alfvén speed, V_A , around $1.3 V_A$, although V_D can reach values as high as $2.5 V_A$ in some cases. Since both V_D and V_A decrease with increasing heliocentric distance, their ratio remains rather constant.

Alpha particles (i.e., fully ionized helium atoms, He^{2+}) represent the second most abundant ion population, accounting for 20% of the solar wind mass density, although their number density ratio with respect to protons is generally found to be around 4% in the fast solar wind (Neugebauer & Snyder 1962, 1966; Asbridge et al. 1974; Yermolaev & Stupin 1997; Kasper et al. 2007). Marsch et al. (1982a) have reported anisotropic alpha particle VDFs with $T_{\parallel} > T_{\perp}$, in contrast with proton VDFs (Marsch et al. 1982b). Moreover, alpha particles also move faster than the proton core population in the fast wind and their drift is of the order of the Alfvén speed (Marsch et al. 1982a; Neugebauer et al. 1996). No differential speed has been seen in the typical slow wind (Kasper et al. 2008; Maruca et al. 2012). Alpha particles also display higher temperatures than protons, with their ratio being generally between four and five in the fast wind (Kasper et al. 2008; Maruca et al. 2013), or even larger (Feldman et al. 1974; Neugebauer 1976; Feynman 1975). For the slow wind, which is more isothermal, this ratio peaks around one (Kasper et al. 2008; Maruca et al. 2013).

The turbulence properties also show remarkable differences between the two types of wind. In the fast solar wind, the large amplitude Alfvénic fluctuations typically populate the low-frequency range of the power spectrum, where a $1/f$ power law is observed (Matthaeus & Goldstein 1986). Correspondingly, the inertial-range Kolmogorov turbulence, characterized by the typical $f^{-5/3}$ spectra, has larger amplitude fluctuations than in the slow wind. This is also in agreement with the larger energy transfer rate measured through the Politano-Pouquet law for the scaling of the mixed third-order moment (Politano & Pouquet 1998), which is valid in both types of wind (Marino & Sorriso-Valvo 2023). Furthermore, at 1 AU the slow wind is more intermittent than fast wind (Sorriso-Valvo et al. 1999, 2023; Bruno et al. 2003), and this characteristic is associated with the emergence of localized, intense small-scale structures (Frisch 1995).

Helios had already shown that fast wind streams at solar minimum are dominated by plasma outflowing from the meridional extensions of the polar coronal holes, with the slow wind coming from regions apparently associated with the boundaries of the hole, the quiet sun, and the streamer belt. At solar maximum, this description breaks down, in the sense that coronal holes are more randomly distributed on the Sun, and the whole heliospheric structure is much more complicated with the apparent slow-fast dichotomy not so well-defined.

The dichotomy itself has been questioned by several authors (von Steiger et al. 2008; Zhao et al. 2009; Stakhiv et al. 2015; Xu & Borovsky 2015; Camporeale et al. 2017; Ko et al. 2018;

Stansby et al. 2020; D'Amicis et al. 2019). D'Amicis et al. (2011), indeed, identified examples of highly Alfvénic slow wind streams, suggesting that the bulk speed is not always a univocal indicator to discriminate different solar wind regimes. Alfvénic slow wind streams share several similarities with the fast wind (D'Amicis et al. 2019, 2020, 2021; Stansby et al. 2020; Perrone et al. 2020), except for the bulk speed. Their solar source, for instance, is an open field region, such as the boundaries of polar coronal holes or low-latitude small coronal holes (Wang 1994), characterized by strongly diverging and over-expanded field lines. Panasenco & Velli (2013) and Panasenco et al. (2019, 2020) argued that, in such topological configurations, with particular emphasis on so-called pseudostreamers, the fast wind might be slowed down, setting the condition for the origin of the Alfvénic slow wind. Pseudostreamers, contrary to the helmet streamers separating opposite polarity regions on the Sun, are closed magnetic field configurations surrounded by open magnetic flux which is all of the same sign. Often-times, the magnetic field in the vicinity of the stalk undergoes large, non monotonic expansion, that could explain the lower wind speed. Understanding how Alfvénic slow wind is (or it is not) accelerated and evolves could provide insight into the general problem of solar wind acceleration.

Recently, an increased occurrence of Alfvénic slow solar wind has been observed in the inner heliosphere, notably from near the coronal boundaries at 10 solar radii to the Earth's orbit, thanks to the new solar mission Parker Solar Probe (Fox et al. 2016). Indeed, since the first encounter, Parker Solar Probe was embedded in several Alfvénic slow wind intervals (see, e.g., Woolley et al. 2021), allowing for the investigation of their characteristics in the environment very close to the Sun. These intervals have strongly been characterized by the presence of large deflections of the magnetic field, namely switchbacks (Dudok de Wit et al. 2020), linked to the local increase of the radial solar wind speed (Horbury et al. 2020a). These features are almost Alfvénic in nature and appear as S-shaped magnetic structures traveling at higher speeds away from the Sun than the background wind (McManus et al. 2020; Telloni et al. 2022).

Another fundamental mission to explore the inner heliosphere is the ESA/NASA Solar Orbiter mission (Müller et al. 2020), launched in February 2020. Solar Orbiter represents a great opportunity to unravel the interrelation between the Sun and the heliosphere taking advantage of coordinated remote sensing and in situ observations for the first time on the same s/c in the inner heliosphere. One of the aims of the mission is to address the solar sources of the solar wind, with particular reference to the slow wind, and its evolution. In this respect, to answer significant questions regarding the origin and formation of the slow solar wind, the Slow Solar Wind Connection Solar Orbiter Observing Plan (Slow Wind SOOP, Zouganelis et al. 2020; Yardley et al. 2023) was developed to extensively exploit the suite of remote-sensing and in situ instruments on board the Solar Orbiter mission. For instance, the paper by Yardley et al. (2023), shows the first example of how plasma and magnetic field measurements of solar wind detected by Solar Orbiter in the inner heliosphere are traced back to their multiple solar sources by using a combination of coronal magnetic field and magnetic connectivity models (Rouillard et al. 2020) and SPICE (SPICE Consortium 2020; Fludra et al. 2021) composition analysis of the solar atmosphere. During the time period analyzed (1–9 March 2022) fast, Alfvénic slow and slow solar wind streams were observed to originate from a coronal hole-active region (CH-AR) complex. The solar wind velocity decreased

throughout the period consistent with the increase in the expansion of the open magnetic field across the CH-AR complex, with the highly Alfvénic slow wind being associated with the over-expansion of the core field of the AR complex.

After the Earth Gravity Assist Maneuver occurred on 26 November 2021, Solar Orbiter started its nominal mission, characterized by several close solar encounters around 0.3 AU. In this paper, we focus on the characterization of solar wind fluctuations, soon after the beginning of the nominal phase, during one of the perihelia, by comparing different solar wind regimes.

2. Observations

This study focuses on Solar Orbiter observations of several Alfvénic intervals during the first perihelion passage of the nominal phase that occurred in March 2022. Solar Orbiter plasma data were provided by the Proton and Alpha Particle Sensor (PAS) which is one of the sensors of the Solar Wind Analyzer (SWA) plasma suite (Owen et al. 2020), dedicated to measuring the 3D velocity distribution functions (VDFs) of protons and alpha particles. We used L2 PAS ground moments (i.e. number density, velocity vector, and temperature from the pressure tensor trace) computed from the VDFs at 4 s resolution. In particular, L2 PAS data products refer to protons only, obtained removing alpha particles by cutting the 1D distribution at the saddle point between the two populations. Magnetic field measurements were provided by the Magnetometer (MAG) instrument (Horbury et al. 2020b), averaged at the plasma sampling time. Data are available on the Solar Orbiter Archive¹. Velocity and magnetic field components are given in the heliographic Radial-Tangential-Normal (RTN) coordinate system, where R points away from the Sun toward the spacecraft, T is the cross product of the Sun's spin axis and R , and N completes the right-handed triad.

Figure 1 shows an overview of the time series of relevant parameters observed by Solar Orbiter from 17 March to 08 April (from DoY 76 to 98), 2022, during which the s/c was at heliocentric distances below 0.4 AU from the Sun. In particular, Fig. 1 shows, from top to bottom: solar wind bulk speed, V_{sw} [km/s]; the heliocentric distance, R [AU]; the correlation coefficient of velocity and magnetic field components ($v-b$) computed at 30 min scale using a running window, C_{VB} ; the radial component of the magnetic field, B_R (black), and magnetic field magnitude, B [nT] (blue); the proton number density, n_p [cm⁻³]; the proton temperature, T_p [K]; the angle the magnetic field forms with the velocity field, Θ_{VB} [deg]. The value of C_{VB} is computed at a typical Alfvénic scale (Tu et al. 1989), that is where large-amplitude and weakly-compressible velocity and magnetic field fluctuations show a high degree of correlations. This scale is chosen only for the preliminary selection of the intervals. In Sect. 4, a spectral analysis allows us to identify the full Alfvénic range for the different streams.

The time interval from DoY 76 to 91 (which correspond to March 17–31) is characterized by slow wind streams, with a bulk speed that, on average, does not exceed 400 km/s. The remaining part is mainly characterized by a fast wind stream with a main portion with a bulk speed exceeding 600 km/s, followed by a rarefaction region where the bulk speed drops to 300 km/s. Alfvénic slow streams, in the first part of the interval, are separated by more standard (non-Alfvénic) slow wind. Indeed, a high C_{VB} with a well-defined sign identifying a well-defined magnetic field (inward) polarity is typical of Alfvénic slow wind inter-

vals. On the contrary, a fluctuating C_{VB} passing from positive to negative values is associated with non-Alfvénic slow intervals. The two solar wind regimes are also characterized by different amplitudes in velocity fluctuations, that are found to be larger in Alfvénic slow streams.

The present analysis is based on the comparison of the selected intervals identified by the gray boxes, showing portions of different solar wind regimes. 'AS1', 'AS2' and 'AS3' identify portions of Alfvénic slow wind while 'F' is a fast wind interval. The gray box in this case is limited to the portion of the stream preceding a transient event although even after the transient event the features of the fast stream show similar behavior. Table 1 shows the average bulk parameters for the selected intervals. Overall, the time series of the magnetic field polarity shows four heliospheric current sheet crossings, although all selected streams have the same polarity corresponding to an outward interplanetary magnetic field and are characterized by low compressibility, that is almost constant proton number density and magnetic field magnitude (see also Fig. 8). The AS1 and AS2 streams have similar average bulk speed (around 400 km/s) while the one associated with AS3 is closer to 300 km/s.

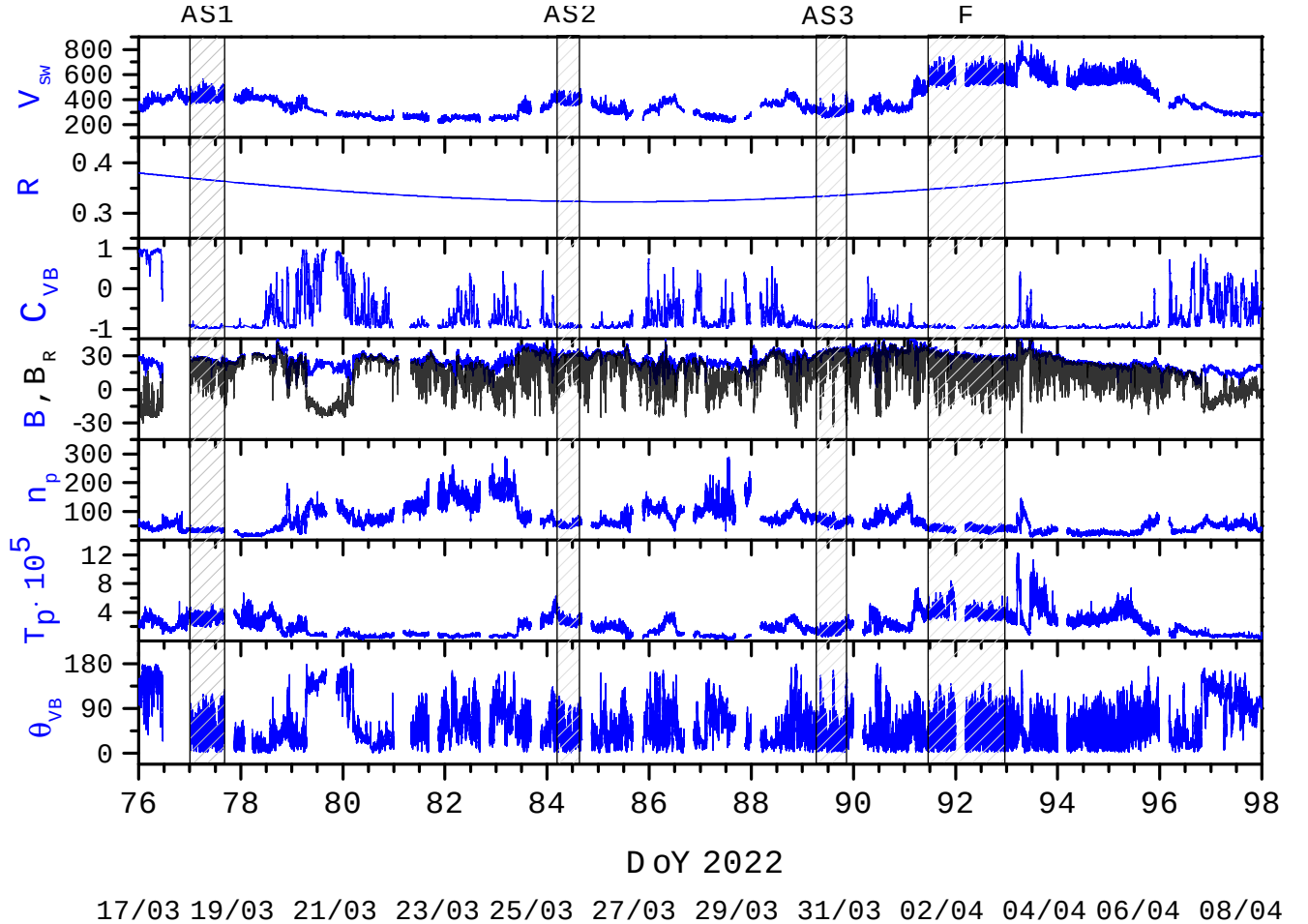
The time interval from DoY 78 to 84 (March 19–25) between AS1 and AS2 was analyzed by Baker et al. (2023) and found to be connected to a narrow open field corridor, forming part of the S-web, producing some extreme properties in their associated solar wind stream. Although Baker et al. (2023) provides a good example of a connectivity study, the interval studied in their paper was not selected for analysis here, as it did not satisfy the requirement of having not only high $v-b$ correlations, but also high-amplitude fluctuations.

All Alfvénic intervals display the well-known property that, despite variations in the B components are large ($dB/B \sim 1$), the total field magnitude stays approximately constant. This property is known as spherical polarization (Barnes & Hollweg 1974), as it geometrically means that the B vector is constrained on a constant radius sphere (e.g. Bruno et al. 2001; Matteini et al. 2015). This characteristic of highly Alfvénic fast wind is also typical of slow Alfvénic streams, especially in the inner Heliosphere (e.g. Woolley et al. 2020; McManus et al. 2020; Matteini et al. 2024). As a consequence, during Alfvénic periods, the magnetic field displays large excursions from the background direction, indicated by the large variability in the Θ_{BV} angle, where the flow can be considered essentially radial (second panel from bottom), which correspond to almost pure rotations ($|B| \sim \text{constant}$). At times, $\Theta_{BV} > 90^\circ$, meaning that fluctuations on the constant B sphere lead to local reversals in the magnetic field polarity; these correspond to changes of sign in the B_R components. It is worth pointing out that, not only the B_R component changes sign along the structure, but also the other components can vary (Dudok de Wit et al. 2020). These features are called switchbacks and are present in all intervals (see Fig. 1) with amplitudes comparable to the magnitude of the magnetic field (Matteini et al. 2015; Borovsky 2016; Horbury et al. 2018; Bale et al. 2019). Although already observed at 1 AU by ISEE-3 (Kahler et al. 1996) and ACE (Gosling et al. 2009; Li et al. 2016) as well as by Helios around 0.3 AU (Borovsky 2016; Horbury et al. 2018), the recent observations by PSP have drawn new attention to this topic for the ubiquitousness of switchbacks inside 0.2 AU (for a review see Raouafi et al. 2023). Our observations show that the amplitude and frequency of switchbacks in the fast wind are larger than in the Alfvénic slow wind intervals. However, a more detailed analysis is beyond the scope of this paper and will be the focus of a follow-up study.

¹ <https://soar.esac.esa.int/soar/>

Table 1. Bulk parameters averaged over the selected intervals including the plasma beta, β .

Interval	Begin	End	R [AU]	V_{sw} [km/s]	n_p [cm ⁻³]	T_p [10 ⁵ K]	B [nT]	θ_{VB} [deg]	β
AS1	2022-03-18T00:00:00	2022-03-18T15:50:24	0.37	417	35.4	3.29	26.9	39.3	0.576
AS2	2022-03-25T06:00:00	2022-03-25T16:19:12	0.32	386	59.8	3.20	31.4	44.4	0.733
AS3	2022-03-30T04:48:00	2022-03-30T22:00:00	0.33	313	69.5	1.67	33.4	41.1	0.376
F	2022-04-01T12:00:00	2022-04-03T00:00:00	0.35	572	39.8	4.19	30.3	45.4	0.652

**Fig. 1.** Overview of time series of relevant solar wind parameters observed by Solar Orbiter at a heliocentric distance ranging between 0.4 and 0.32 AU. From top to bottom: solar wind bulk speed, V_{sw} , in km/s; heliocentric distance, R , in AU; v - b correlation coefficient computed at 30 min scale using a running window, C_{vB} ; radial component of the magnetic field, B_R , in nT (black) and magnetic field magnitude, B , in nT (blue); number density, n_p , in cm⁻³; proton temperature, T_p , in K; angle the magnetic field forms with the velocity field, Θ_{BV} , in degree. The boxes identify the intervals investigated in this study corresponding to portions of Alfvénic slow wind (AS1, AS2, AS3) and fast wind (F).

A clear indication of the presence of Alfvénic fluctuations in in situ measurements is given by the presence of correlations between velocity and magnetic field components. In ideal conditions, $\delta V = \pm \delta b$, where δb is given in Alfvén units (i.e. $b = B / \sqrt{\mu_0 \rho}$, with μ_0 and ρ the magnetic permeability and mass density, respectively). It is important to remark that, in L2 data, the mass density refers only to the contribution given by protons. If we represent in a scatter plot the two quantities, we should in principle expect to find a linear relationship with slope equal to 1. However, previous studies have shown that this does not really apply to observations (e.g. [Bavassano & Bruno 2000](#)). To characterize the Alfvénicity of fluctuations, velocity fluctuations are compared with the corresponding magnetic field fluctuations, in

Alfvén units. In order to select the most Alfvénic part of the fluctuations, we mainly focus on the NT plane, without considering the radial component R , which is the least Alfvénic one and in particular, in the following, we show scatter plots relative to the normal component only, which is more Alfvénic than the other two components ([Tu et al. 1989](#)). Figure 2 shows the v - b correlations corresponding to the normal component only. The linear fit, computed for each stream, provides information on its energy balance. Indeed, from the fit we can derive the Pearson's correlation coefficient, CC, and the slope, γ . The fits were computed using a standard least squares method. The errors associated to the slope are computed with a 95% confidence level. γ is equivalent to the square root of the Alfvén ratio, r_A , where

$r_A = e^V/e^B$, e^V and e^B being the kinetic energy and magnetic energy, respectively. r_A measures the energy imbalance of solar wind fluctuations. Although the different Alfvénic streams are characterized by comparable high level of correlations (similar CC values, close to 1), they are characterized by different energy imbalance as shown in the different panels of Fig. 2. For the three Alfvénic slow streams, the absolute value of their slope is less than 1 leading to r_A equal to 0.60, 0.41, 0.50, respectively, indicating imbalance in favor of magnetic energy. The bottom panel, referring to fast wind, on the contrary, returns $r_A = 0.93$, very close to equipartition of energy.

3. Solar sources

The magnetic connectivity of the different streams to their solar sources was investigated using the potential field source surface (PFSS) extrapolation of Schrijver & De Rosa (2003): the magnetic field is assumed to be potential from the photosphere out to a spherical surface, situated for the present calculations at $R = 2.5 R_\odot$ from Sun center, where the field is assumed to become radial. The PFSS extrapolation allows for assimilation of data from SDO/HMI with a 6 hour cadence and includes a flux-dispersal model, evolving the field over the full solar photosphere. The PFSS model has two intrinsic limitations: the approximation of the solar coronal field as potential and the source surface imposed at fixed height. This first approximation becomes harder and harder to justify as the field is mapped ever lower into the corona and into the transition region and chromosphere. There currents may be strong and the field line mapping becomes extremely complex. However the validity of source region identification at the corona may be assessed by comparing the PFSS field-line structure with images (see, e.g., Panasenco & Velli 2013; Panasenco et al. 2019, and references therein) and allowing the source surface to deviate from a spherical shape when required to match field polarity and intensity with in situ observations (see, e.g., Panasenco et al. 2020). To locate the potential source regions of the solar wind measured at Solar Orbiter, the spacecraft position is first extrapolated backward to the source surface ballistically (i.e. using a constant solar wind speed). The speed chosen is the measured solar wind speed at the spacecraft during the interval: for the intervals identified by Fig. 1, this is slowly variable with values ranging from 313 to 572 km/s.

Figure 3 shows the PFSS B^2 contour maps and solar wind magnetic foot-points along Solar Orbiter trajectories for the four different Alfvénic intervals studied here. The upper panel refers to the PFSS maps and solar wind source of the March 18 and 25 streams while the lower panel to the March 30 and April 2 streams. The direct instantaneous projection of the s/c location is shown by squares. Crosses indicate the ballistic backward mapping onto the source surface: as stated, the measured in situ solar wind speed is used; however, to accommodate for uncertainties in the solar wind acceleration profile and possible errors in measurements, as well as to assess the stability of the PFSS backward mapping, the ballistic projection is calculated also by adding or subtracting up to ± 80 km/s, in bins of 10 km/s, explaining the multiple crosses. This amounts to considering a maximum possible error in the transport time from the Sun to Solar Orbiter of about $\pm 250\%$. From the crosses on the source surface, the location of the source is obtained mapping downward along the PFSS determined magnetic field lines. The contours of equal magnetic field pressure are shown for heights $R = 1.2 R_\odot$ and $R = 1.1 R_\odot$ for the upper and lower panel respectively. Green indicates open magnetic field regions with positive polarity while the neutral

line is in black bold. The choice for the contour heights is made for clarity, as going down to the surface leads to very strong magnetic field concentrations that render reading the contour map very difficult.

Notice how in some instances the mapping from crosses to the circles leads to essentially one position (top panel, March 18th and bottom panel, April 2nd) corresponding to streams AS1 and F. Stream AS2 is intermediate, the source drifting along the coronal hole for different ballistic projection speeds, while AS3 clearly straddles a pseudostreamer configuration, so the ballistic projections fall in the open regions on either side of the streamer stalk. This is more clearly visible in the rotated field-line view provided in Figure 4. This image also shows that the field lines at the source are expanding rapidly in 3D, as they not only expand over the pseud-streamer but also bend strongly out of the plane. High expansion is a feature of all three slow Alfvénic streams, but not of the fast stream on April 2nd. While it is very clear for AS3, it is less so for AS1 and AS2.

The source region of the chosen streams is illustrated using images taken by the Solar Dynamics Observatory (SDO) Atmospheric Imaging Assembly (AIA) in the 193 Å passband (Figure 5). The top two panels show the origins of streams AS1 and AS2, while the bottom two panels show the source region of AS3 and F respectively. AS1 would be probably considered by an “active region wind”, in the sense that it is coming from a region neighboring an active cluster as shown in Figure 5, top left panel, light blue oval. As an open region surrounded by closed field it expands rapidly above the closed regions, though less so than AS2 and AS3, which most likely explains why its properties are closest to the fast wind stream F. AS2 is from a narrow coronal hole extension, (right panel), also expanding rapidly, while AS3 is from the pseudostreamer arising in the oval in the bottom left panel. The fast wind F originates from well inside the coronal hole, bottom right panel red oval. It is clear that some of the observed differences in characteristics of the plasma and turbulence must arise from the differing origins.

4. Spectral analysis

The solar wind is a multi-scale magneto-fluid (Verscharen et al. 2019). Observations by Helios have shown that the Alfvénic range typically extends from tens of minutes to some hours and generally evolves with the heliocentric distance (e.g. Tu & Marsch 1995; Bruno & Carbone 2013). To fully characterize the range where fluctuations are Alfvénic, we compute the power spectral density (PSD) of velocity and magnetic field fluctuations.

Power spectra of velocity and magnetic field fluctuations are described by power laws over a wide frequency range. In Alfvénic intervals, at least three different frequency ranges can be observed. At large scales, or low frequencies, a debated f^{-1} regime, corresponding to fluctuations of the large scales of the turbulent cascade characterizes the spectrum (Matthaeus & Goldstein 1986; Dmitruk & Matthaeus 2007; Verdini et al. 2012; Matteini et al. 2018; Bruno et al. 2019; D'Amicis et al. 2020; Perrone et al. 2020). At intermediate frequencies, the so-called inertial range is typically described by a turbulence spectrum (as first observed by Coleman 1968), which is generally described by the Kolmogorov scaling $f^{-5/3}$ (Kolmogorov 1941), or by the Iroshnikov-Kraichnan scaling of $f^{-3/2}$ (Iroshnikov 1963; Kraichnan 1965). It has been recently suggested that magnetic field fluctuations show an evolution from a $-3/2$ to a $-5/3$ spectral slope moving away from the

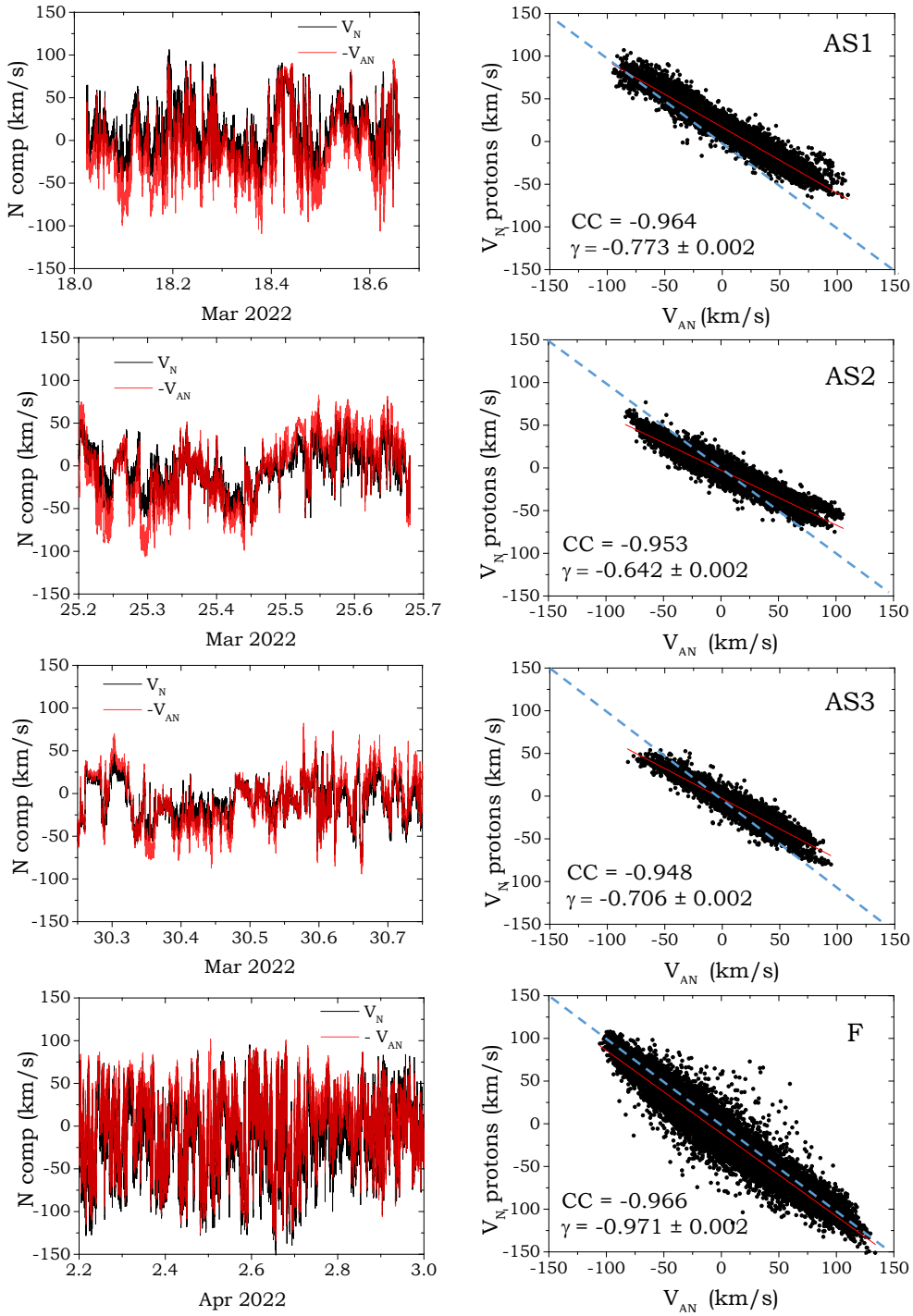


Fig. 2. Time series of the N components of velocity, V_N (black line), and magnetic field (in Alfvén units), $-V_{AN}$ (red line), for the different Alfvénic streams (left panels), highlighting the v - b correlations and corresponding to L2 PAS data. For the same streams, the scatter plots of the same components are displayed in the right panels, along with the Pearson correlation coefficients, CC and slopes, γ , of the linear fits (solid red lines). Derived Alfvén ratios, r_A , are the following: 0.60, 0.41, 0.50, 0.93, moving from upper to lower panel. The ideal slope equal to -1 , indicating equipartition of energy, is shown as a blue dashed line. Explanation in the text on how r_A is related to γ .

Sun (e.g. [Chen et al. 2020](#)), while velocity fluctuations are well-described by an Iroshnikov-Kraichnan scaling of $-3/2$ within 1 AU ([Podesta et al. 2006, 2007](#); [Salem et al. 2009](#); [Borovsky 2012](#); [D'Amicis et al. 2020](#)), and evolve toward $-5/3$ at larger heliocentric distances ([Roberts 2010](#)). Around proton scales, spectra steepen due to kinetic effects ([Leamon et al. 1998](#); [Kiyani et al. 2015](#)). The frequency of the break typically evolves with radial distance, while the kinetic range spectral index and

intermittency are highly variable (e.g., see a recent review by [Bruno 2019](#), and references therein).

Figure 6 shows the PSD of the trace of B and V (upper and lower panels, respectively), obtained through Fast-Fourier Transform (gray lines) and through the Welch method (colors). The observed frequencies span the injection range and the inertial range, due to the limitation imposed by the plasma resolution that does not allow to capture the kinetic range. This is

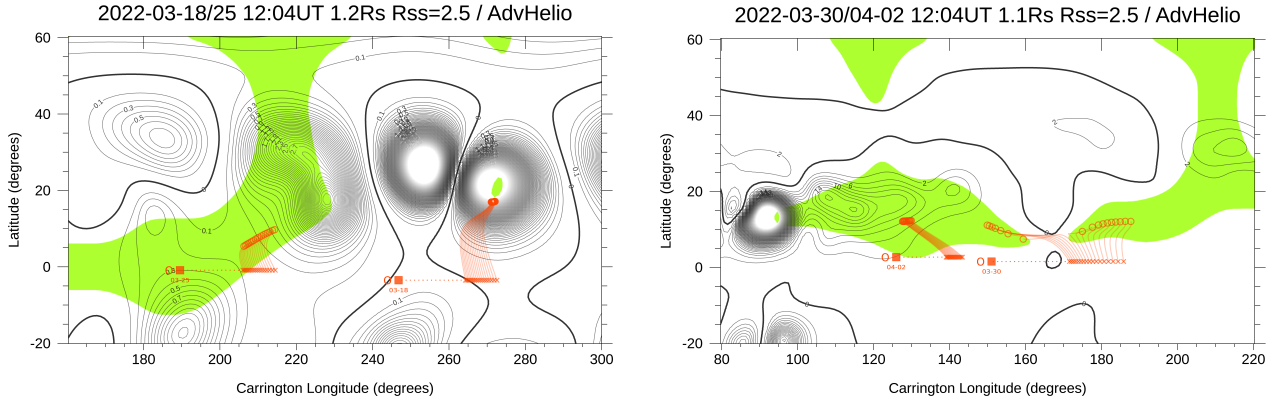


Fig. 3. Potential field source surface B^2 contour maps and solar wind magnetic foot-points along Solar Orbiter trajectories (red) for the selected intervals. The projection of the s/c location (squares) on the source surface (crosses) and down to the solar wind source region (circles). The maps are magnetic pressure iso-contours calculated for the heights $R = 1.2 R_{\odot}$ and $R = 1.1 R_{\odot}$ (chosen to make the magnetic field contours clearer). The crosses result from ballistic mapping using the measured in situ solar wind speed ± 80 km/s in bins of 10 km/s. Open magnetic field regions are shown in green (positive polarity) while the neutral line is in black bold.

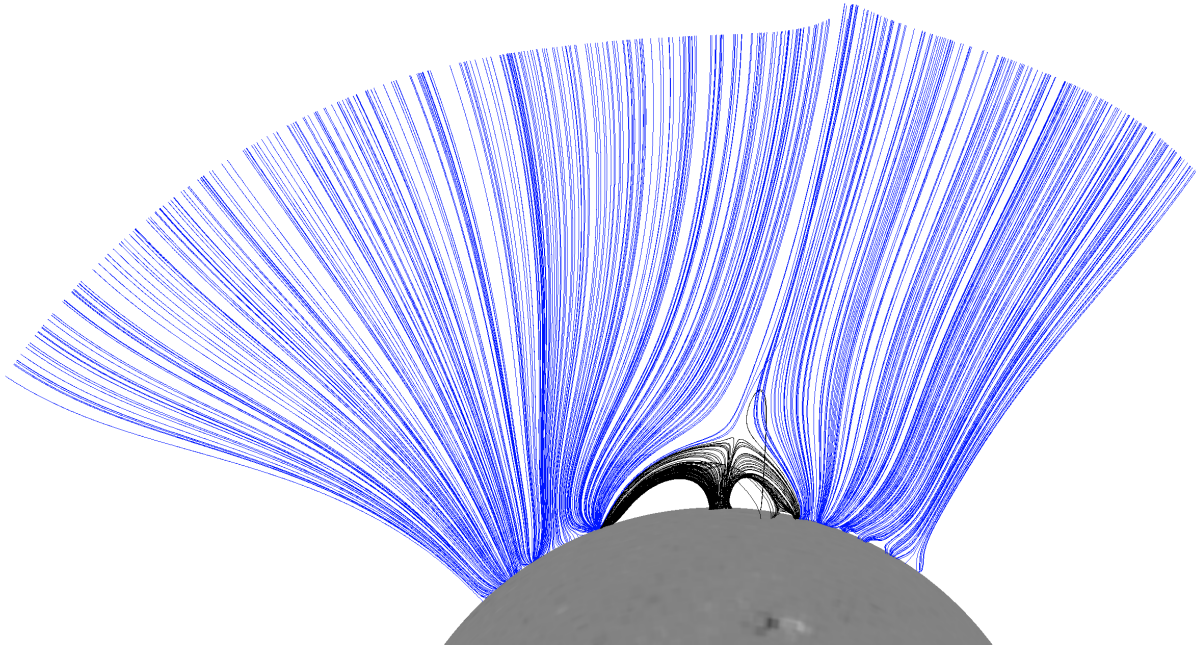


Fig. 4. 3D potential field source surface model of the pseudostreamer for AS3 interval. The modeling made along the area selected in Figure 5, bottom left panel. The PFSS pseudostreamer model was rotated to the limb view.

also confirmed by the values of the characteristic frequencies shown in Table 2. In particular, we computed: the cyclotron frequency, Ω_c ; the frequencies associated with the proton Larmor radius $\lambda_L = V_{th}/\Omega_c$; the proton inertial length $\lambda_i = V_A/\Omega_c$ and the resonant condition $\lambda_R = (V_A + V_{th})/\Omega_c$ (Bruno & Trenchi 2014). The Taylor hypothesis, which is valid for the samples under study, is used to convert spatial scales to temporal scales (Taylor 1938). Therefore, all these characteristic lengths can be derived from the parameters shown, taking into account that we can switch from the spatial domain to the frequency domain using $f = V_{sw}/(2\pi\lambda)$, where f and λ are the generic characteristic frequency and length. Table 2 shows all the characteristic speeds, necessary to compute the characteristic frequencies. These are all found above 10^{-1} Hz.

The left panels of Fig. 6 display the PSDs of magnetic field fluctuations, providing information about the occurrence of $-3/2$

and/or $-5/3$ scaling. To highlight this point, we indicate characteristic scales of possible occurring spectral breaks with vertical lines and slopes fitted on the PSDs in each sector. Since the difference sought in the slope is very slight and is usually difficult to detect in experimental samples of solar wind, we have included piecewise compensated spectra in the bottom of each panel of Fig. 6 to highlight the robustness of the obtained slopes. Interestingly, while the higher frequency part of the spectrum is well approximated by a fluid-like scaling, that is $-5/3$, an intermediate frequency range fairly compatible with the Iroshnikov-Kraichnan scaling $-3/2$ of the isotropic Alfvénic turbulence emerges. This observation suggests a scenario in which large-scale Alfvénic turbulent fluctuations evolve in a fluid-like regime at higher frequencies. This fact is discussed more in detail in association with intermittency and turbulent energy transfer rate features reported in the following sections. The lower frequency

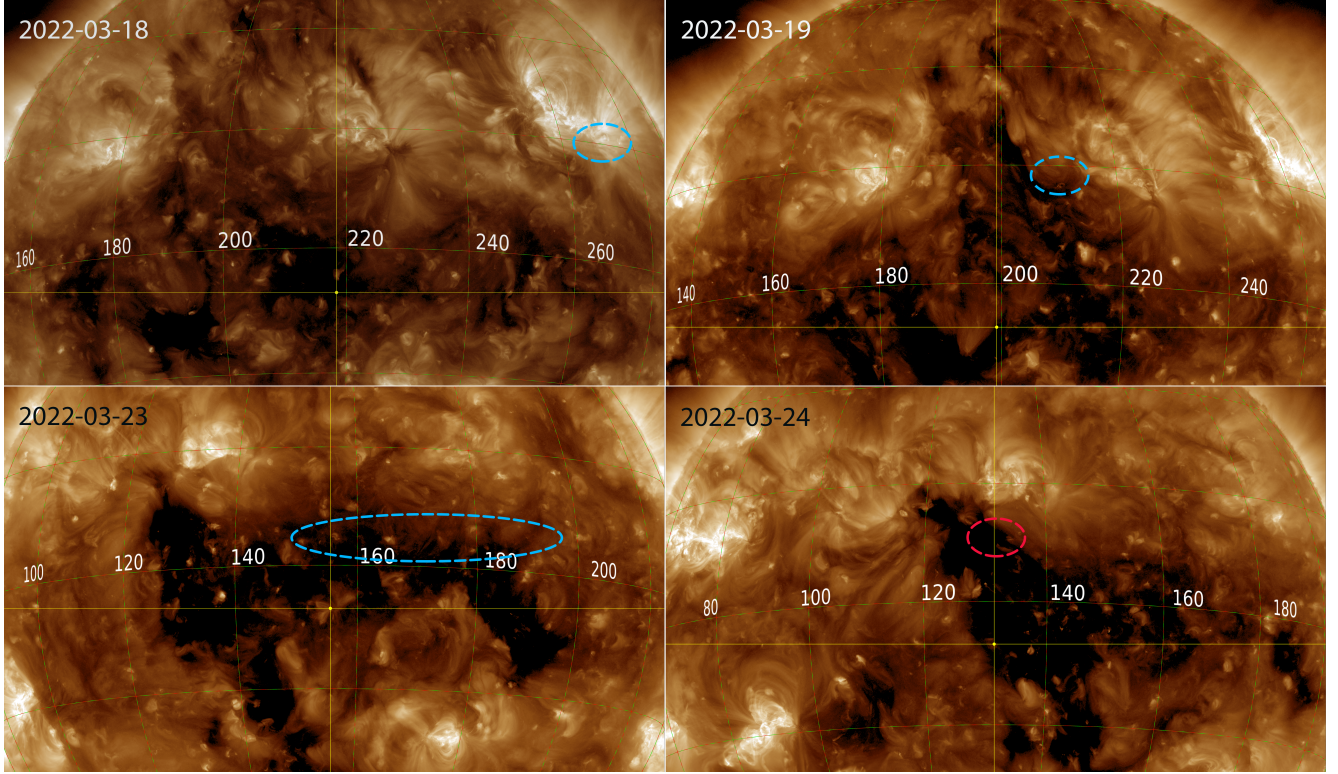


Fig. 5. Images from SDO/AIA of the 193 Å band showing the corona and source regions of the different solar wind streams described in the paper. Top left, AS1, top right AS2, bottom left AS3, bottom right F. The image dates, reported in the panels, were chosen to best display the source region on the Sun. Dashed regions are the projection of the s/c location down to the solar wind source region.

part of the magnetic field PSD is characterized by a flatter trend, displaying slopes ranging $\sim[-1.0, -1.2]$.

Power-law fits of velocity PSDs are also illustrated in the right panels of Fig. 6. In this case the PSDs tend to flatten at higher frequency due to the onset of instrumental noise. Velocity fluctuations show a $\sim[-1.0, -1.2]$ trend at low frequency, similar to B , and tend toward a $-3/2$ PSD slope at high frequencies, taking values slightly lower than $-3/2$ at intermediate frequencies depending on the data sample. Whereas a small range of scales has been used to fit the power laws of V at high frequencies for the Alfvénic slow wind data samples, in the case of the fast wind we do not show the fit since the range is strongly affected by instrumental noise, due to the extremely small range of available frequencies. Table 3 provides a summary of all results from the PSD analysis, including the time scales associated with the lower ($\Delta t_>$) and higher ($\Delta t_<$) frequency spectral breaks, as well as the slopes of the PSD (α_3 for the lower frequency range, α_2 for the intermediate frequency range, and α_1 for the higher frequency range) obtained for both B and V .

We also computed power spectra of the trace of B and V fluctuations normalized to $\langle B \rangle$ and $\langle V_A \rangle$ ($\delta B(f)/\langle B \rangle$ and $\delta V(f)/\langle V_A \rangle$, respectively) as in, e.g., Bruno et al. (2019), D'Amicis et al. (2020, 2022), to further characterize and compare the fluctuations of the different streams. We derived the relative amplitude of the fluctuations from the Fourier analysis performed in Fig. 6 using the following relationship: $\delta B(f)/\langle B \rangle = \sqrt{2fS_B(f)}/\langle B \rangle$ for magnetic field, where $S_B(f)$ is the Fourier spectrum of B . In the same way, we derived $\delta V(f)/\langle V_A \rangle$. The normalized power spectra ($\delta B(f)/\langle B \rangle$ and $\delta V(f)/\langle V_A \rangle$) in the upper and lower panels, respectively, are shown in Fig. 7. According to this normalization, we can easily derive Kolmogorov and the Kraichnan scaling. Indeed, since $S_B(f) \sim f^{-5/3}$, $\delta B(f)/\langle B \rangle \sim f^{-1/3}$

Table 2. Characteristic speeds and frequencies of the different Solar Orbiter samples.

Interval	V_{sw} [km/s]	V_A [km/s]	V_{th} [km/s]	Ω_c [Hz]	f_L [Hz]	f_i [Hz]	f_R [Hz]
AS1	417.	98.6	73.7	0.41	0.48	0.28	0.16
AS2	386.	88.6	72.7	0.48	0.40	0.33	0.18
AS3	313.	87.4	52.5	0.51	0.48	0.29	0.18
F	572.	104.	83.2	0.46	0.50	0.40	0.22

for the Kolmogorov scaling. In a similar way, $\delta V(f)/\langle V_A \rangle \sim f^{-1/4}$ (since $S_V(f) \sim f^{-3/2}$) for the Kraichnan scaling. These are shown as dashed lines in the two panels. Normalized spectra show that at large scales, where spectra have a slope closer to -1 , the amplitude is roughly constant through scales and close to $\delta B/B \sim 1$. In the fast wind, a similar level of normalized fluctuations is observed for the velocity, with $\delta V/V_A \sim \delta B/B$, while in the other streams the normalized level of velocity fluctuations is smaller, consistent with their lower Alfvén ratio (larger imbalance between kinetic and magnetic energy).

The correlation coefficient C_{VB} reported in Fig. 1 and used to identify Alfvénic solar wind intervals, has been computed at the fixed scale of 30 minutes. In the following we investigate the full Alfvénic range performing a spectral analysis. It must be noted that the range of Alfvénic characteristic scales can vary, depending not only on the type of solar wind regime but also on the distance from the Sun (Tu et al. 1989). Although this study is not focused on the radial evolution, it is worth mentioning this aspect since this suggests to compare the results of the present analysis

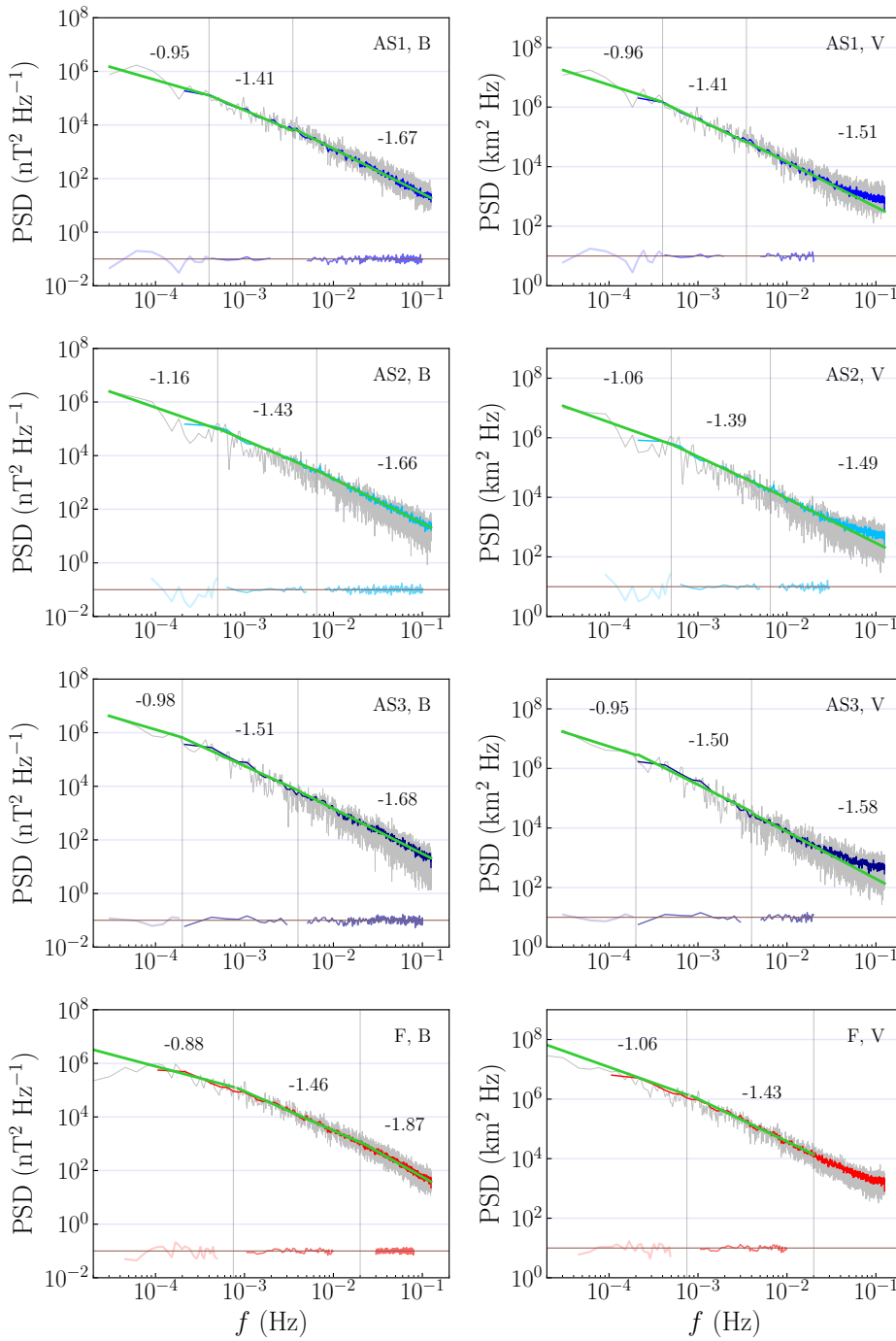


Fig. 6. Power spectral density of the trace of magnetic field and solar wind velocity, left and right panels respectively, for AS1 (blue), AS2 (cyan), AS3 (dark blue), and F (red) data intervals. The PSDs are shown in gray (without smoothing) and colors (Welch method). Green solid lines indicate the PSD best fit along with their scaling exponent. Vertical lines mark the different frequency ranges where PSD fit are performed, corresponding to possible spectral breaks identified from PSD traces of the magnetic field. Colored lines in the bottom of each panel indicate the piecewise compensated spectra for each sector. High-frequency regions where velocity PSDs flatten due to instrumental noise are excluded from the fit.

with previous observations (e.g. Helios) at the same heliocentric distance.

Marsch & Tu (1990a) studied the radial evolution of MHD turbulence in the inner heliosphere using observations by Helios between 0.3 and 1 AU using Elsässer variables (Elsässer 1950). The latter represent a useful tool to investigate the Alfvénic content of solar wind fluctuations (Tu et al. 1989; Grappin et al. 1991). Elsässer variables are defined as: $z^{\pm} = V \pm b$, where b is the magnetic field vector in Alfvén units for a background magnetic field pointing toward the Sun, while $z^{\pm} = V \mp b$ for the opposite polarity. This definition allows one to always identify z^{+} with outward propagation modes (with respect to the Sun) and z^{-} with inward fluctuations. Marsch & Tu (1990a) investigated the spectral features of the Elsässer variables, thus in the

frequency domain. Such an approach would allow us to study the extent of the Alfvénic range. Indeed, after computing the three components of z^{+} and z^{-} , respectively, we computed the PSD of the trace of their components, $e^{\pm}$ vs. f , that basically identifies the energy associated with these propagating modes. We then derived the normalized cross-helicity in the frequency domain: $\sigma_c(f) = (e^{+}(f) - e^{-}(f)) / (e^{+}(f) + e^{-}(f))$, that measures the predominance of z^{+} on z^{-} or vice versa. σ_c equal to 1 (−1) indicates the presence of only the outward (inward) component, while $|\sigma_c| < 1$ corresponds to a mixture of inward and outward modes and/or non-Alfvénic fluctuations (Bruno & Carbone 2013).

We then computed the trace of the power spectral density of V (here indicated as $e^V(f)$ that basically corresponds to the bottom panel of Fig. 6), and b in Alfvén units, $e^b(f)$. The ratio

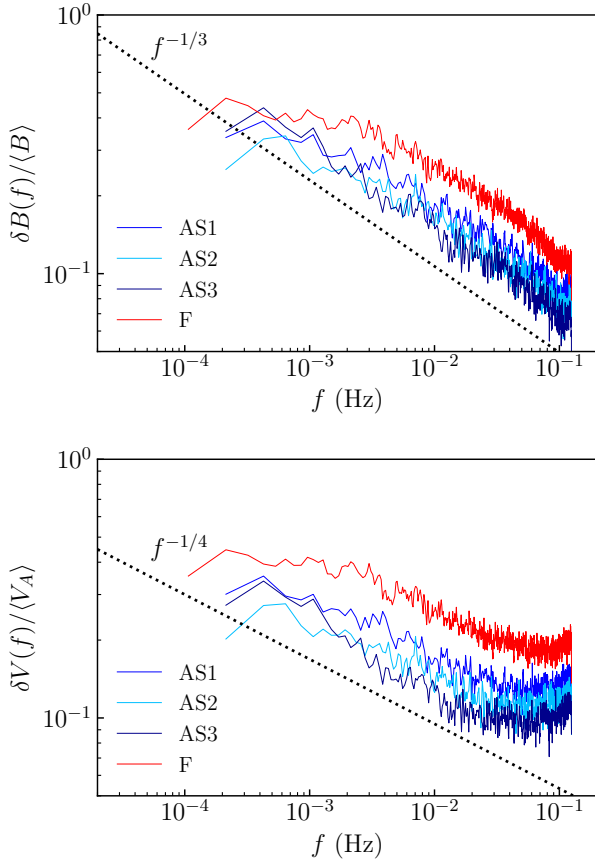


Fig. 7. Power spectral density of the trace of magnetic fluctuations normalized to the average magnetic field (upper panel) and velocity fluctuations normalized to the average Alfvén speed (lower panel). Characteristic power laws ($f^{-1/3}$ and $f^{-1/4}$) are shown as dashed lines for reference. The color indicates the different streams with the same color code used in Fig. 6.

between these two quantities allows to evaluate the imbalance between kinetic and magnetic energy, as measured by the Alfvén ratio (see Sect. 2) or by the normalized residual energy in the frequency domain, $\sigma_R(f) = (e^V(f) - e^B(f))/(e^V(f) + e^B(f))$. σ_R is linked to r_A by $(r_A - 1)/(r_A + 1)$. It must be noted that σ_R equal to +1 (−1) indicates the absence of magnetic (kinetic) fluctuations, while equipartition of energy holds for $\sigma_R = 0$ (or $r_A = 1$) as it is the case for pure Alfvénic fluctuations (Tu & Marsch 1995). These tools have been widely used in similar studies (e.g. Bavassano et al. 1998, 2000; Bruno et al. 2007; D’Amicis et al. 2007, 2011; D’Amicis & Bruno 2015, and references herein).

Figure 8 shows the power spectra of σ_C (upper panel) and σ_R (middle panel) for the different streams (same color code used throughout the paper). As already mentioned in the introduction, Alfvénic turbulence is characterized not only by v – b correlations but also by weak compressibility, meaning that fluctuations in the magnitude of the total magnetic field are much smaller than the magnetic field fluctuations – fluctuations are in a state referred to as spherical polarization (Bruno et al. 2001; Matteini et al. 2015). For this reason we show also magnetic compressibility in the bottom panels, defined as the ratio between the PSD of the magnitude of magnetic field over the trace of PSD of the magnetic field components.

The comparison between the different streams highlights a slightly different extension of the Alfvénic range. The most Alfvénic interval is the fast stream showing not only the highest

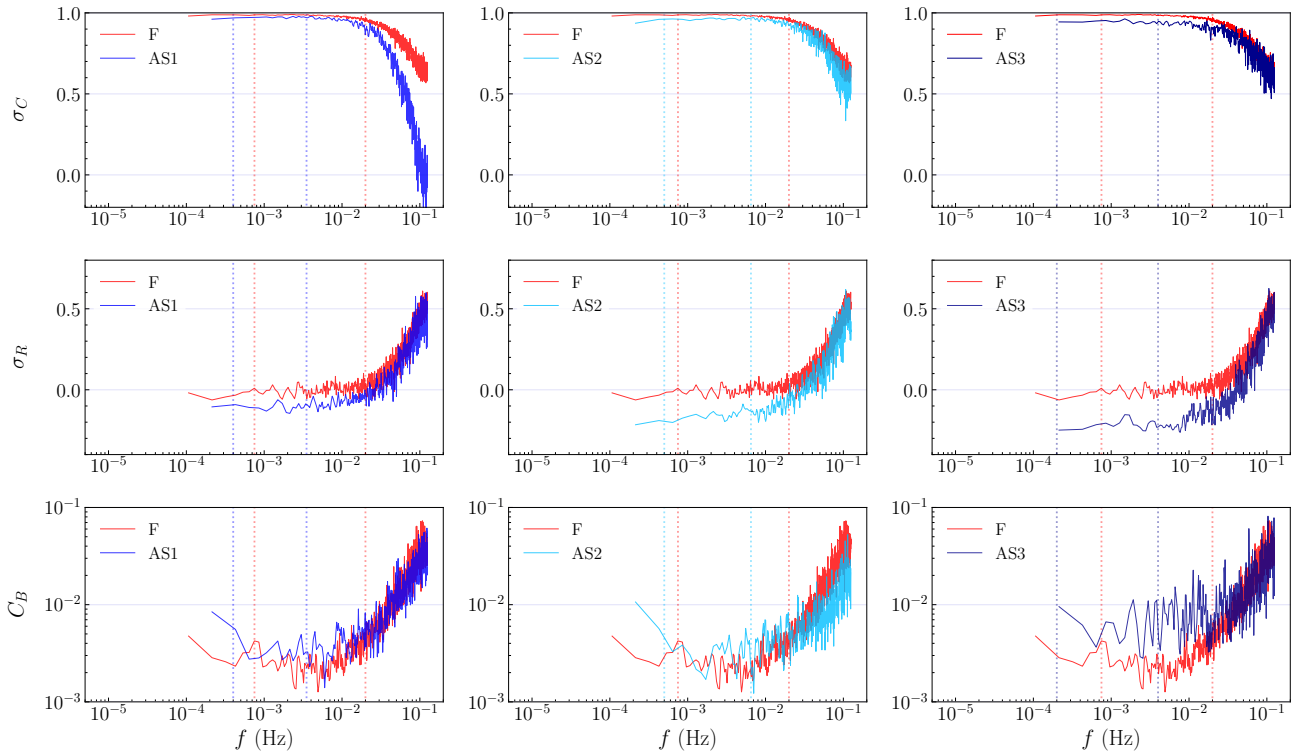
σ_C values in the most extended frequency range but also fluctuations characterized by energy equipartition. AS1 keeps σ_C values above 0.8 for frequencies below 2×10^{-3} Hz and then it is characterized by a strong decrease toward values below 0.6. AS2 is similar to the fast wind in a large range of frequencies and it starts to deviate for frequencies above 4×10^{-3} Hz. Also AS3 is similar to the fast wind up to 2×10^{-3} Hz and then it decreases slowly and it remarkably keeps high values at high frequencies at odds with the other intervals. The frequency associated with spectral breaks identified in magnetic field PSDs, Figure 6, are here reported for reference. The negative values of σ_R observed in the middle range for all the Alfvénic slow data samples highlight the dominance of magnetic energy suggesting that Alfvén waves are more important in the energy cascade, thus leading to the $-3/2$ spectral slopes. Otherwise, at higher frequencies, where kinetic energy starts to prevail, we are in presence of a fluid-like cascade which is in agreement with the observed $-5/3$ spectral slopes. However, high frequency part of both σ_C and σ_R spectra must be taken with some caveats since instrumental noise may affect velocity measurements. The frequency ranges identified in our studies are well within what was observed by Tu & Marsch (1995) at almost the same heliocentric distance, although our results extend to higher frequencies, corresponding to scales of the order of minutes, thanks to the higher temporal resolution of the PAS instrument.

The different energy balance between fast and Alfvénic slow wind streams, with the fast wind closer to equipartition of energy, is in agreement with a previous study by D’Amicis et al. (2022), although the latter was performed at L1. To properly compare our findings with those in D’Amicis et al. (2022), we should take into account that Alfvénicity evolves with the heliocentric distance (Marsch & Tu 1990a). The effect of the radial evolution involves both a shift toward lower frequencies (say larger times scales) of the Alfvénic range and a decrease in the magnitude of σ_R (and the tendency of r_A to be less than 1). Although σ_R is very close to 0 near the Sun (0.3 AU), especially in the fast wind, it remarkably decreases with increasing heliocentric distance (e.g., Bruno et al. 1985; Marsch & Tu 1990a), reaching an asymptotic value around 1 AU. The departure from energy equipartition has been attributed to the turbulence evolution (see e.g. Grappin et al. 1991; Roberts et al. 1992), to the effect of solar wind structures (Tu & Marsch 1993) or also to effects of pressure anisotropy and ion differential streaming (Bavassano & Bruno 2000).

As shown in D’Amicis et al. (2022), particular attention should be paid to interpret the high-frequency part of the spectrum. Indeed, the tendency of σ_C to approach 0 or become negative is linked to a flattening of e^- rather than a decrease of e^+ (not shown here). Tu et al. (1989) proposed a generation mechanism based on the parametric decay of e^+ in the high-frequency range (Galeev & Oraevskii 1963) to explain the flattening notice in e^- spectrum at high frequency. In this model, large amplitude Alfvén waves decay into two oppositely propagating Alfvén modes and a sound-like wave moving with the pump wave, with most energy going into the sound-like fluctuation and the backward Alfvén mode. Marsch & Tu (1990b) have shown that a part of the inward fluctuations may be compressive in nature and perhaps be related to magnetoacoustic wave or composed of pressure-balanced structures (Goldstein & Siscoe 1972) and the fine stream tubes (Thieme et al. 1987). Bruno et al. (1989) also stated that a decrease of the cross helicity is often accompanied by the appearance of strong compressive fluctuations in the magnetic field rather than the local generation of inward propagating Alfvénic modes. Moreover, Bruno & Bavassano (1993)

Table 3. Spectral break frequencies and slopes of magnetic field PSD traces.

Interval	$\Delta t_{<} [s]$	$\Delta t_{>} [s]$	α_3	α_2	α_1
AS1 (<i>B</i>)	286	2500	-0.95 ± 0.21	-1.41 ± 0.08	-1.67 ± 0.01
AS1 (<i>V</i>)	286	2500	-0.96 ± 0.20	-1.41 ± 0.07	-1.51 ± 0.05
AS2 (<i>B</i>)	154	2000	-1.16 ± 0.44	-1.43 ± 0.06	-1.66 ± 0.01
AS2 (<i>V</i>)	154	2000	-1.06 ± 0.40	-1.39 ± 0.05	-1.49 ± 0.05
AS3 (<i>B</i>)	250	5000	-0.98 ± 0.23	-1.51 ± 0.09	-1.68 ± 0.01
AS3 (<i>V</i>)	250	5000	-0.95 ± 0.17	-1.50 ± 0.09	-1.58 ± 0.05
F (<i>B</i>)	50	1333	-0.88 ± 0.13	-1.46 ± 0.03	-1.87 ± 0.02
F (<i>V</i>)	50	1333	-1.06 ± 0.09	-1.43 ± 0.03	–

**Fig. 8.** Power spectra of the normalized cross-helicity σ_C (upper), the normalized residual energy σ_R (middle), and magnetic compressibility C_B (lower) for the different Alfvénic slow wind streams compared to the fast wind. Vertical dotted lines, drawn with the same color of the associated stream, indicate the frequencies associated with spectral breaks of $S_B(f)$ reported in Figure 6.

clearly showed the role of compressive fluctuations on the cross-helicity level. According to Tu & Marsch (1991), the spectrum of e^- would be caused by the so called magnetic field directional turnings (MFDTs) in the hypothesis of an interplanetary turbulence mainly made of outwardly propagating Alfvén waves and convected structures represented by MFDTs. Moreover, while Grappin et al. (1990) demonstrated a strong correlation and suggested a cause-effect relationship between inward-oriented Alfvénic fluctuations and relative density fluctuations, we wonder how much we can trust the authenticity of these density fluctuations. It is important to consider that De Marco et al. (2020) showed that instrumental effects can introduce significant spectral and kinetic features, which previous studies have mistakenly attributed solely to physical mechanisms. This underscores the need for more cautious interpretation of such features in this type of analysis. This evidence has already been emphasized in previous observations by Helios at almost the same heliocentric distances by Marsch & Tu (1990a). A similar argument can be used to explain the tendency of σ_R to

become positive. In this case, for $f > 0.04$ Hz, the instrumental noise affecting e^V , rather than a decrease of e^b , would cause a flattening of e^V (see also Fig. 6), thus determining positive σ_R values that do not correspond to a real kinetic energy excess at high frequency.

5. Intermittency

One of the most characterizing aspects of turbulent flows is intermittency. In fully developed turbulence, it refers to the inhomogeneity of the energy transfer, which results in the accumulation of energy on sparse and clustered small-scale, highly-energetic structures, where most of the dissipation takes place (Frisch 1995). As a result, the statistical properties of the field fluctuations are scale-dependent, with the emergence of high tails in the distribution functions that highlight the progressive accumulation of energy toward localized small-scale structures. Intermittency in solar wind plasmas was extensively studied (Sorriso-Valvo et al. 1999), revealing substantial dependence on,

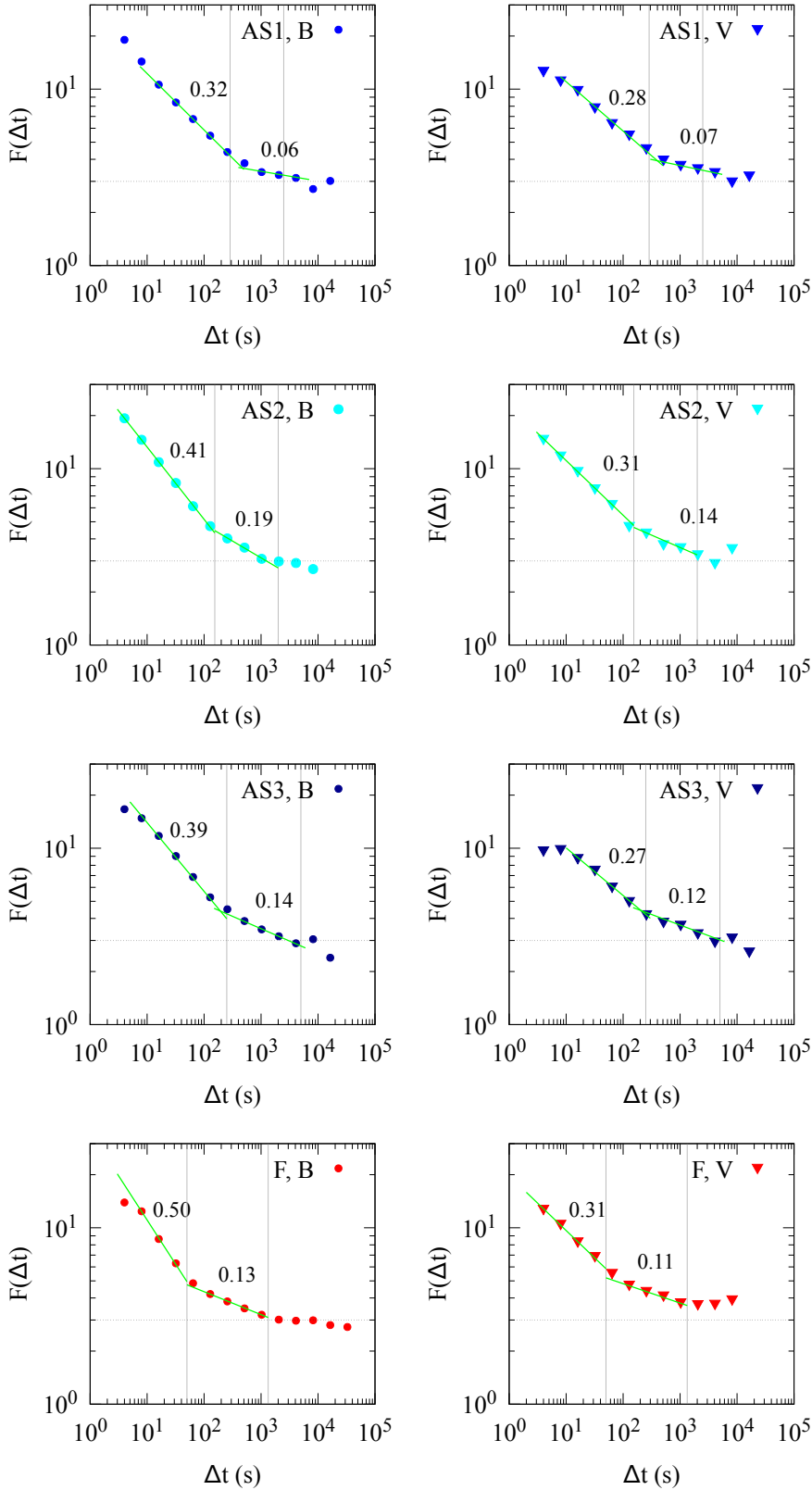


Fig. 9. Flatness of magnetic field (left) and velocity (right), averaged over the three vector components. Vertical lines mark the frequency breaks observed in the spectra. The scaling exponents κ are indicated where a power-law fit was performed (green lines, extended beyond the fitting range to better identify the break scales). The horizontal lines indicate the Gaussian value $F = 3$. Color code as in Figure 6.

among other factors, type of solar wind, radial distance, and solar activity (Bruno 2019).

The simplest diagnostics for a quantitative evaluation of intermittency is the flatness of the distribution function, as measured through the normalized fourth-order moment of the fluctuations. The flatness is defined, for a generic field ψ , as $F(\Delta t) =$

$\langle \Delta \psi^4 \rangle / \langle \Delta \psi^2 \rangle^2 \sim \Delta t^{-\kappa}$. In fact, since the moments of the fluctuations show power-law scaling, generated by the global scaling invariance of the MHD equations, the flatness also displays a power-law scale dependence in the inertial range. Its value typically increases from the Gaussian reference $F = 3$ at large scale, where the fluctuations are not correlated via nonlinear

Table 4. Turbulence parameters for the selected intervals.

Interval	κ_1 (B)	κ_2 (B)	κ_1 (V)	κ_2 (V)	ε [kJ m ⁻¹ s ⁻¹]
AS1	0.32 ± 0.01	0.06 ± 0.01	0.28 ± 0.01	0.07 ± 0.01	27 ± 3
AS2	0.41 ± 0.01	0.19 ± 0.01	0.31 ± 0.01	0.14 ± 0.05	180 ± 30
AS3	0.39 ± 0.01	0.14 ± 0.01	0.27 ± 0.02	0.12 ± 0.02	80 ± 10
F	0.50 ± 0.02	0.13 ± 0.01	0.31 ± 0.02	0.11 ± 0.01	4000 ± 400

interactions, to larger values at small scales, where dissipation and other non-MHD processes break the scale invariance. The scaling exponent κ can be used as a measure of intermittency, and is related to the multifractal properties of the field (Carbone & Sorriso-Valvo 2014).

Figure 9 shows the scale-dependent flatness for both magnetic field and velocity, for the four selected intervals. Since all components displayed similar trends, for the sake of simplicity we show the flatness averaged over the three components. In all cases, two power-law scaling ranges within the classical MHD inertial range emerge clearly, separated by a sharp break. The scaling exponents obtained through power-law fits are indicated in each figure, and collected in Table 4, being labeled as κ_1 and κ_2 in the small- and large-scale ranges, respectively. Vertical lines indicate the location of the spectral breaks observed in Figure 6, which roughly correspond to the breaks in the flatness (albeit with some discrepancy, particularly evident for AS1). We note that, unlike for the power spectra, clear breaks are observed for the velocity as well, at scales compatible with the magnetic field breaks. This could be due to the fact that higher-order moments are dominated by small-scale, strong intermittent fluctuations that emerge from the background and therefore are less sensitive to the instrumental noise. At scales between a few seconds and approximately 100 s, a steep scaling is observed, with exponents between 0.27 and 0.50. These are indicative of strong intermittency, and are in agreement with values obtained in solar wind samples at similar distance from the Sun (see, e.g., Sorriso-Valvo et al. 2023). On the other end of the inertial range, between ~100 s and approximately 1 hour, shallower power laws are observed with exponents between 0.06 and 0.19. Such exponents are closer to the typical values observed in neutral flows ($\kappa \approx 0.1$, see for example Anselmetti et al. 1984). The different exponents observed in this range indicate a different regime, and that the nonlinear interactions generate a cascade with different properties. In both ranges, velocity fluctuations are consistently less intermittent than magnetic field ones, in agreement with previous observations (Sorriso-Valvo et al. 1999; Bruno et al. 2003) and with numerical simulations of MHD turbulence (Sorriso-Valvo et al. 2000).

The emergence of a characteristic scale, here located between one and a few minutes (see Table 4), suggests that a change in the dynamics may be present. The break in the scaling laws was already observed at similar scales in fast solar wind magnetic field and velocity measurements from Helios 2 (Sorriso-Valvo et al. 2023) and in PSP data (Hernandez et al. 2021; Sioulas et al. 2023; Wu et al. 2022), and seems to be a robust, yet still unexplored, property of the Alfvénic solar wind. Among possible causes, it could be due to residual sweeping effects from the large-scale Alfvénic fluctuations in the lower-end portion of the inertial range, which might reduce the efficiency of nonlinear interactions. It could also be related to the coronal magnetic structure resulting from the photospheric horizontal motions associated with supergranulation, as suggested by recent observations from the Parker Solar Probe (Bale et al.

2021, 2023; Horbury et al. 2023). Another possibility encompasses the role of expansion in driving and constraining the turbulence. However, the nature of the observed scaling range is not clear, and deserves to be studied in more detail.

6. Energy transfer rate

In collisionless space plasmas, the rate at which energy is transferred across scales by the turbulent nonlinear interactions can be estimated using third-order scaling laws. As in the case of neutral flows (see Frisch 1995, and references therein), in the inertial range a linear scaling relation exist for the mixed third-order moments of the fields increments. Under the hypotheses of statistical homogeneity, local isotropy, high Reynolds' number and incompressibility, the Politano-Pouquet (PP) law predicts: (Politano & Pouquet 1998)

$$Y(\Delta t) \equiv \langle \Delta V_L (|\Delta \mathbf{V}|^2 + |\Delta \mathbf{b}|^2) - 2\Delta b_L (\Delta \mathbf{V} \cdot \Delta \mathbf{b}) \rangle = \frac{4}{3} \varepsilon V_{sw} \Delta t, \quad (1)$$

with the subscript L indicating longitudinal increments of a field in the sampling direction and the brackets sample average. In the right-hand side, ε indicates the energy transfer rate of the turbulence cascade, while the wind bulk speed, V_{sw} , is used to switch from spatial scales to time scales, as allowed by the validity of the Taylor hypothesis (we note that this transformation also reverses the sign of the right-hand side of Equation (1)). Initially validated in MHD numerical simulations (Sorriso-Valvo et al. 2002; Mininni & Pouquet 2009) and then in the ecliptic (MacBride et al. 2005) and high-latitude (Sorriso-Valvo et al. 2007) solar wind, the above relation is routinely used to establish the presence of a well developed turbulent cascade and to estimate the energy transfer rate (see Marino & Sorriso-Valvo 2023, and references therein). Although several modified versions of the PP law allow in some occasions to relax part of the hypothesis to adapt to solar wind conditions, the basic linear law in Equation (1) is often sufficient to describe the Alfvénic solar wind (Marino & Sorriso-Valvo 2023), and provides a first-order estimate of the turbulence energetics.

In order to determine the state of the turbulence, we estimated the mixed third-order moments $Y(\Delta t)$ for the four samples of Alfvénic solar wind. Results are shown in Fig. 10. For all the intervals, a roughly linear scaling can be observed in the range between approximately 3 and 100 seconds. This confirms that, at least in that range of scales, a nonlinear turbulent cascade can be considered as fully developed. Incidentally, such a range roughly corresponds to the smaller-scale portion of the inertial range, where the steepest spectra (i.e., closer to the Kolmogorov scaling $-5/3$) and flatness scaling are observed, as described in Sections 4 and 5, which is indicative of a more developed turbulence.

The mixed third-order moments in Equation (1) can be fitted to a linear relation to obtain the energy transfer rates ε ,

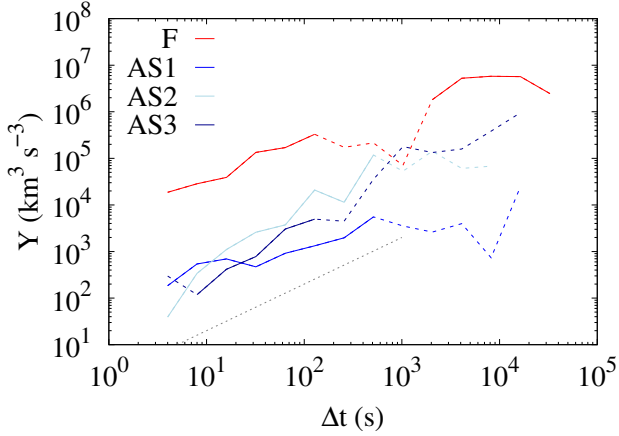


Fig. 10. Scaling of the third-order moments $Y(\Delta t)$, Equation (1), for the four intervals. Solid and dashed lines indicate positive and negative moments, respectively. The gray dotted line shows a reference linear relation. For all intervals, a roughly linear positive scaling exists in the range from ~ 5 to ~ 100 s or over. Color code as in previous figures.

which are collected in Table 4. The quite remarkable variability of the energy transfer rate can be attributed to different solar wind local conditions. In particular, the radial distance from the Sun (see Table 1, Wu et al. 2022; Brodiano et al. 2023; Sorriso-Valvo et al. 2023), the large-scale cross-helicity (see Fig. 8, Smith et al. 2009) and the amplitude of the large-scale fluctuations (see the spectral amplitude in Fig. 6, Sorriso-Valvo et al. 2021) do not seem to be relevant parameters in this case. As clearly seen in Fig. 10, in the fast wind sample the energy transfer is one or two orders of magnitude larger than for the slow intervals. This is in agreement with previous observations (Sorriso-Valvo et al. 2023), and with the larger spectral power seen in Fig. 6. On the other hand, for the three slow wind samples larger energy transfer rate seems to be associated with larger intermittency, as measured by the scaling exponent of the magnetic field and velocity flatness in the same range of scales, κ_1 (see Table 4, Sorriso-Valvo et al. 2021; Márquez Rodríguez et al. 2023). Since larger intermittency typically suggests more developed turbulence and enhanced dissipation, the above correlation might be interpreted in terms of a more efficient turbulent cascade, which would have both larger intermittency and energy transfer rate.

It should be noted that the values of the energy transfer rate have to be taken with some degree of approximation. Indeed, in this work we used a simplified version of the PP law that may be missing contributions from, for example, anisotropy (Marino & Sorriso-Valvo 2023). Furthermore, the high-frequency noise on velocity measurements might affect the range in which we estimated the energy transfer rate, although the increasing flatness at small scales seems to suggest that such noise do not affect high-order moments considerably, since these are dominated by strong fluctuations that will have a higher signal-to-noise ratio. Moreover, the three slow wind samples presented here are insufficient to disentangle possible other reasons for the observed ordering, for which a more systematic statistical study should be performed.

Around scales of approximately 100 s, the linear scaling does not hold anymore. In most cases, the third-order moment changes sign, indicating some features or change of dynamics, which is again in agreement with the observation of a distinct scaling of the flatness in this range. The observation of a linear scaling range in the region where the spectrum seems com-

patible with Kolmogorov and the flatness has a steeper scaling is, again, consistent with previous observations of Helios 2 data (Sorriso-Valvo et al. 2023), and confirms the observation that the range of scales traditionally described as an inertial range of turbulence might be interrupted by a characteristic scale separating two different turbulence regimes.

7. Possible role of the different ion populations in determining the Alfvénic content of the fluctuations

In the previous sections, we have investigated plasma properties using L2 plasma moments available on the SOAR archive that refer to the proton population only and are obtained removing alpha particles by cutting the 1D distribution in velocity space at the saddle point between the two populations. However, it is possible to investigate the behavior of the $v-b$ correlations in the different solar wind main ion populations, namely the proton core, the proton beam and the alpha particles. To describe separately ion populations we use an innovative technique based on clustering developed by De Marco et al. (2023) applied directly on the VDFs measured by PAS that are available on the SOAR archive. Using this technique, we are able to separate the 3D VDFs of different ion species and derive the moments (i.e. the bulk parameters) of the different populations. To this aim, we applied De Marco's technique to the full PAS 3D VDFs. The idea is to evaluate the $v-b$ correlations for the three populations and to estimate the energy balance of the fluctuations in each case. Since ion populations have relative drifts with respect to each other, because of the geometry of Alfvénic fluctuations, we expect different plasma components to oscillate with different amplitudes (Goldstein et al. 1995; Matteini et al. 2015), according to the different distance from the origin of the wave frame (Bruno et al. 2024). In this particular frame, there is no electric field acting on the particles, so that their velocity change in direction while the magnitude remains constant.

Figure 11 shows the scatter plots of the normal components of velocity for the proton core and proton beam, $V_{N,c}^p$ (left) and $V_{N,b}^p$ (right), respectively, vs. the normal component of the magnetic field, V_{AN} in Alfvén units. In this section, V_{AN} (and V_A in general) is computed taking into account the contribution of all the three ion populations (see e.g., Bruno et al. 2024). The Pearson correlation coefficient, CC, along with the slope of the fit, γ , represented by the solid red line, are shown in each panel. The blue dashed lines, either $V_{N,c}^p = -V_{AN}$ or $V_{N,b}^p = V_{AN}$, mark equipartition of energy. Figure 11 shows a proton beam with an Alfvénic correlation of opposite sign with respect to that of the proton core, as expected for a minor population drifting relatively to the main proton core (see also Goldstein et al. 1995; Matteini et al. 2015; Bruno et al. 2024). Comparing with Fig. 2, we see that for the proton core almost every stream shows protons in a condition closer to equipartition of energy, with a slope close to 1, apart from the AS2 stream. By contrast, the proton beams shows overall a magnetic energy imbalance. Only the AS2 stream shows proton core and beam with similar CC values (but with opposite signs) and almost similar magnetic energy imbalance, while the other intervals clearly depict a substantial difference between nearly energy-equipartitioned proton core and strongly magnetic energy imbalanced proton beams. All this is consistent with a proton beam streaming ahead of the bulk core protons by more than the Alfvén speed.

To support this interpretation, we computed the histograms of the drift speed of proton beam with respect to proton core,

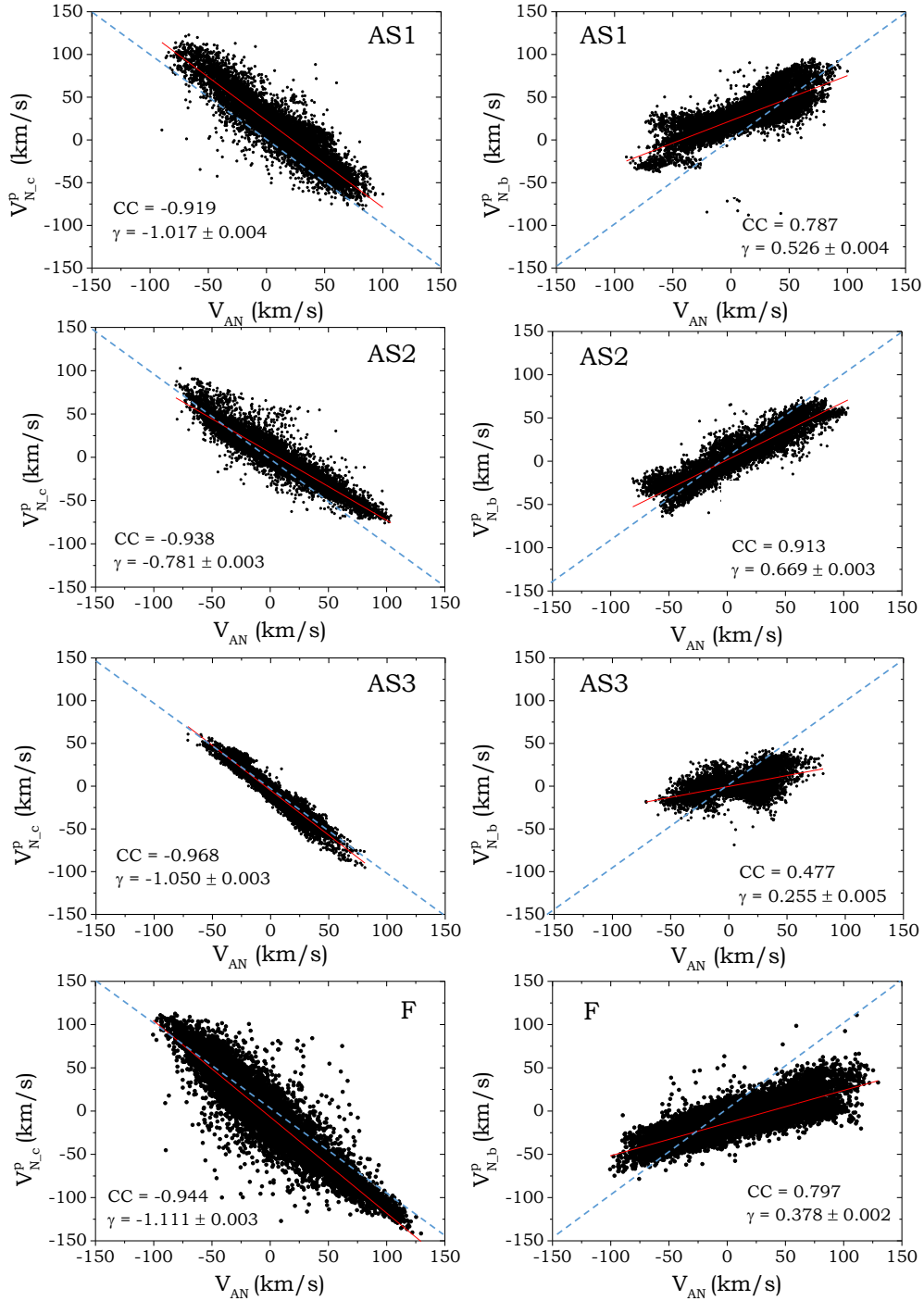


Fig. 11. Scatter plots of the normal components of velocity, $V_{N,c}^p$ (left) and $V_{N,b}^p$ (right), for the proton core and proton beam, respectively, and magnetic field, V_{AN} , in Alfvén units. The Pearson correlation coefficient, CC, along with the slope of the fit, γ , represented by the solid red line, is shown in each panel. The blue dashed line, $V_{N,c}^p = -V_{AN}$ or $V_{N,b}^p = V_{AN}$ is shown for comparison.

$V_{D,b}^p/V_A$ (blue line), normalized to the Alfvén speed, where $V_{D,b}^p$ and V_D^α are defined in the following way: $V_{D,b}^p = |V_c^p - V_b^p|$, V_c^p and V_b^p being the velocity of proton core and beam populations, respectively. Results are reported in Figure 13. We notice how the relative drift between proton core and beam always exceeds V_A .

Similarly, Figure 12 shows the scatter plots of the normal components of velocity of alpha particles, V_N^α , and magnetic field, V_{AN} , in Alfvén units. The Pearson correlation coefficient, CC, along with the slope of the fit (red solid line), are shown

in each panel. The blue dashed lines corresponds to $V_N^\alpha = V_{AN}$ and represents equipartition of energy. Also for alphas, we notice a correlation between magnetic and velocity fluctuations that is opposite with respect to the main proton core. This is consistent with the fact that also alpha particles are streaming faster than the proton core and overall with a drift that is $\geq V_A$.

In Figure 13, we represent also the histograms of the drift speed of proton beam with respect to proton core, $V_{D,b}^p/V_A$ (blue line), normalized to the Alfvén speed, $V_D^\alpha = |V_c^\alpha - V_\alpha^\alpha|$, V_c^α and V_α^α being the velocity of proton core and alpha particles, respectively.

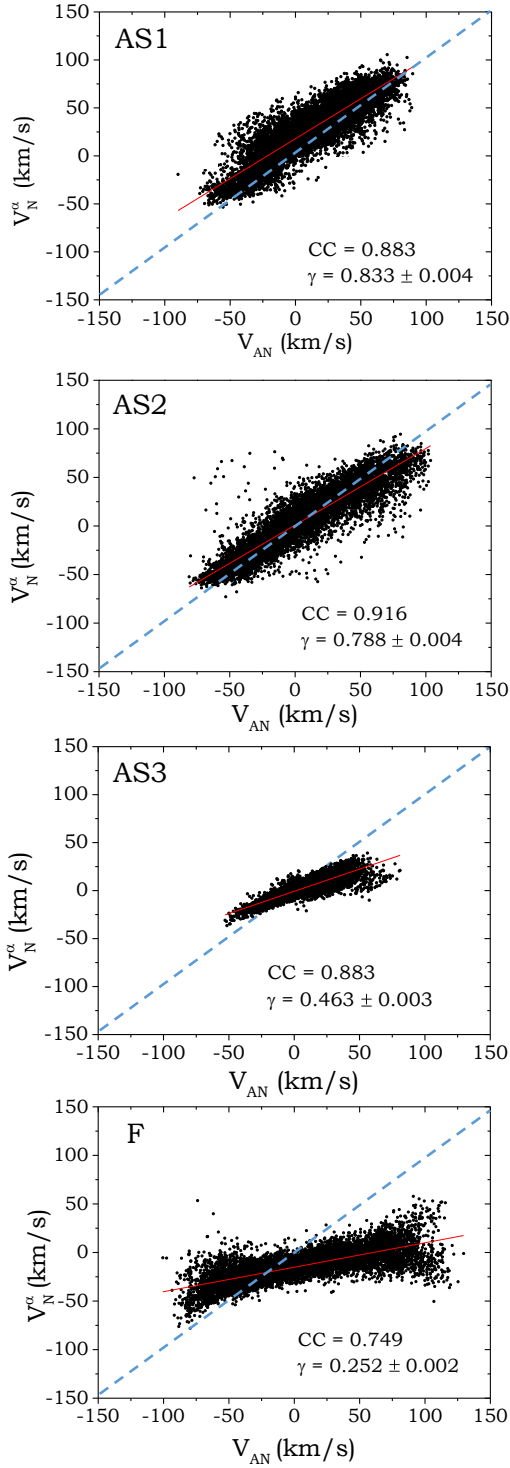


Fig. 12. Scatter plots of the normal components of velocity of alpha particles, V_N^α , and magnetic field, V_{AN} , in Alfvén units. The Pearson correlation coefficient, CC, along with the slope of the fit, γ , represented by the solid red line, is shown in each panel. The blue dashed lines corresponds to $V_N^\alpha = V_{AN}$.

More in detail, in the two upper panels (corresponding to AS1 and AS2 respectively) there is a slope close to 0.8, a condition not too far from energy equipartition. On the other hand, there is a shallower slope in the v - b correlations characterizing the Alfvénic slow wind observed for the AS3 interval, which is probably related to a drift speed closer to V_A , a condition that

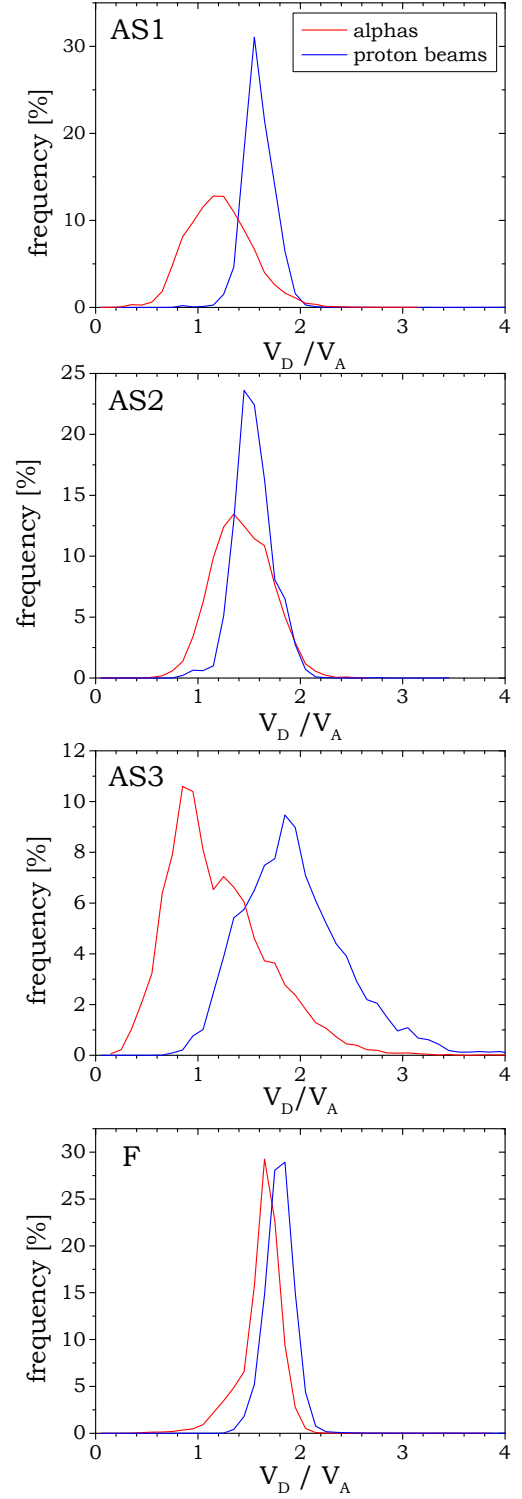


Fig. 13. Histograms of the drift speed normalized to the Alfvén speed. In particular, the blue line shows that of the proton beam respect to proton core, $V_{D,b}^p / V_A$ while the red line shows that of alpha particle respect to proton core, V_D^α / V_A .

makes them stream in phase with the waves (surfing the wave front) with the result that no Alfvénic correlations are found in that case (Matteini et al. 2015).

The same argument cannot be used for the small slope observed in the fast wind (last panel), as according to Figure 13, the alpha drift in this stream is substantially larger than V_A .

It is likely that in this case, one should consider a more complex interplay between alphas and the Alfvénic fluctuations. In fact, the observed v - b correlations in alpha particles, can be also influenced by the internal structure of the alpha velocity distribution and in particular the presence of some large alpha beams (Bruno et al. 2024). Alpha particles are considered here as a single population, while they may indeed also consist of a core and a beam with almost comparable number density. If the two alpha populations are characterized by an opposite sign of correlation that would reduce the resulting observed v - b correlations when the two alpha particle populations are not separated. This would reduce the amplitude of the alpha velocity fluctuations respect to that of the protons, (as extensively discussed in Bruno et al. 2024).

In terms of comparisons with previous works, it is known from the literature that the distribution of the drift speed for the proton beam is quite larger than the local Alfvén speed (Marsch & Livi 1987; Matteini et al. 2013) and, in our case, the peaks of those distributions range between 1.5 and 1.9 V_A , with the largest values corresponding to AS3 and F. The alpha population behaves in a similar way but with a smaller drift speed closer to V_A (Marsch et al. 1982a; Neugebauer et al. 1996); this is consistent with the drift for the Alfvénic slow wind streams in Figure 13. The drift is substantially higher in the fast wind and this is likely due to the presence of a massive alpha beam, which moves faster than V_A (Bruno et al. 2024), further shifting the peak of the distribution toward $V_D/V_A = 1.6$.

8. Conclusions

This paper focuses on plasma and magnetic field observations, performed respectively by SWA/PAS and MAG on board Solar Orbiter, of several Alfvénic intervals close to the first perihelion passage of the nominal phase, occurred at the end of March 2022. This fortuitous circumstance allowed us to characterize solar wind fluctuations and, in particular, to perform a comparative study between a fast wind and three Alfvénic slow wind intervals observed at almost the same heliocentric distance ($\Delta R = 0.05$ AU as maximum radial excursion, see Table 1 and Fig. 1). The different streams were selected on the basis of the Alfvénic content of the fluctuations with particular reference to a high C_{VB} correlation coefficient, almost incompressible conditions and large amplitude fluctuations. In particular, magnetic fluctuations in the radial component also shows the presence of switchbacks in all intervals.

Alfvénic fluctuations were first characterized by comparing velocity fluctuations with the corresponding magnetic field fluctuations in Alfvén units. In particular, the scatter plot of the N component was used to derive a first approximation of the level of correlation and also the energy balance of the fluctuations. This basically gives further information with respect to the time series of C_{VB} shown in Fig. 1, which is very similar for all the intervals. On the contrary, the simple computation of r_A from the slope of the scatter plot allows to identify a remarkable magnetic energy imbalance for the Alfvénic slow wind intervals and a quasi energy equipartition for the fast wind. Moreover, we studied $\sigma_C(f)$ and $\sigma_R(f)$ in the frequency domain to fully investigate the Alfvénic range. With the limitation imposed by instrumental noise especially for the plasma instrument at high frequency, the comparative spectral analysis clearly shows slightly different extensions for the Alfvénic ranges for the different streams. These are in agreement with what was observed by Tu & Marsch (1995) at almost the same heliocentric distance, although our results extend to higher frequencies, say to temporal scales up

to the order of minutes. On the other hand, the spectral analysis also confirms the magnetic energy imbalance of the Alfvénic slow wind intervals highlighted with the scatter plots and already observed in D'Amicis et al. (2022). However, where and why the Alfvénic slow wind departs from energy equipartition and thus shows a different behavior with respect to the fast wind is still not understood and needs further investigation.

In the spectral analysis of magnetic and velocity fields we identified regimes characterized by different spectral slopes. For both magnetic and velocity fields we observed a tendency toward a $\sim 1/f$ range at low frequency. This trend, expected for the fast stream, appears also evident in Alfvénic slow data samples, in agreement with previous findings (D'Amicis et al. 2020, 2021). In the range of scales typically described as the inertial range of turbulence, magnetic field fluctuations exhibit two different spectral slopes, switching from nearly-Kraichnan spectra to Kolmogorov ones. Therefore, the low-frequency part of the inertial range shows a tendency toward a more Alfvénic turbulence, whereas at time scales below ~ 100 s Alfvénic fluctuations are gradually suppressed in favor of a fluid-like turbulent ones. This finding is also supported by the spectral analysis of cross helicity, which shows a deviation from the low-frequency Alfvénic correlation. This is not observed for the velocity fluctuations, which are nonetheless affected by instrumental noise at high frequency, as particularly evident by inspecting the flattening of the PSD. However, since the difference between Kolmogorov and Kraichnan predictions of the spectral slopes is rather small, it is sometimes hard to precisely identify such a variation in empirical PSDs. To this purpose, we complemented the spectral analysis by studying the intermittency of magnetic field fluctuations. Less sensitive to noise, the flatness displays clear double power-law scaling, with breaks compatible with the Kraichnan-to-Kolmogorov transition of the PSD, for both magnetic field and velocity. The slope of the power law increases at scales $\lesssim 100$ s in all the data samples for both magnetic and velocity fields indicating an increased level of intermittency in the fluctuations observed at these scales (Sorriso-Valvo et al. 2023). Finally, we observe that in the fluid-like range of turbulence, viz., up to ~ 100 s, the third-order moments follow the Politano-Pouquet law. By estimating the energy transfer rate associated with different streams we found that the fast wind stream is characterized by an ε which is one to two order of magnitude larger than in the Alfvénic slow data samples.

The comparison between fast wind and Alfvénic slow wind intervals highlights differences between solar wind regimes: the fast wind is characterized by larger amplitude fluctuations and magnetic and velocity fluctuations are closer to equipartition of energy. In fact, the Alfvénic slow wind streams appear to be on a spectrum of wind types, with AS1, originating from open field lines neighboring active regions, displaying some similarities with the fast wind in terms of fluctuation amplitude and turbulence characteristics, but not with respect to the energy content of the alpha particles and beams. With this respect, the slight magnetic energy excess what we observe for protons as a single population ($\gamma = 0.773$) turns to be equipartition of energy for the proton core ($\gamma = 1.017$) and a slight magnetic energy imbalance for the proton beam population ($\gamma = 0.833$). Alpha particles, on the other side, shows a magnetic energy excess ($\gamma = 0.833$) similar to the proton beam.

The other two slow streams differ both in their sources as well as plasma characteristics, with one coming from the expansion of a narrow coronal hole corridor, AS2, and the other, AS3, from a region straddling a pseudostreamer. The latter displayed the coldest, highest density but slowest stream, with smallest

fluctuation amplitude and greatest magnetic energy excess in the proton beam population ($\gamma = 0.255$) while the proton core population is characterized by equipartition of energy ($\gamma = 1.050$). It also showed the largest scatter in proton beam drift speeds and greatest difference in drift speed between proton beam and alpha particles.

As a general comment, when comparing Figs. 2 and 11, we notice that when we separate the proton core from the proton beam, fluctuations are closer to equipartition of energy for the proton core while the proton beam is generally characterized by a large magnetic energy excess. This is something that we intend to further investigate in a future paper along with the energy partition in the alpha population. This may have implication in the spectral analysis and help us to understand better how energy is partitioned in the different ion populations.

These results present a variety of challenges to solar wind models, that must explain how Alfvénicity is maintained in these slow wind intervals originating from widely different sources, while other characteristic plasma properties, including turbulence, vary significantly from one stream to the next. While Solar Orbiter observations, together with the observations from Parker Solar Probe, seem to indicate that Alfvénic fluctuations seem to arise almost everywhere in the early accelerating wind, the reason for the diverse outcomes, in terms of wind acceleration and thermodynamics, as well as turbulence properties, remains to be explored.

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