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Large amplitude fluctuations in the Alfvénic solar wind

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Abstract
Large amplitude fluctuations, often with characteristics reminiscent of large amplitude Alfvén waves propagating away from the Sun, are ubiquitous in the solar wind. Such features are most frequently found within **fast solar wind streams** and most often at solar minimum. The fluctuations found in slow solar wind streams usually have a smaller relative amplitude, are less Alfvénic in character and present more variability. However, intervals of slow wind displaying Alfvénic correlations have been recently identified in different solar cycle phases. In the present paper we report Alfvénic slow solar wind streams seen during the maximum of solar activity that are characterized not only by a very high correlation between velocity and magnetic field fluctuations (as required by outwardly propagating Alfvén modes) - comparable to that seen in fast wind streams - but also by higher amplitude relative fluctuations comparable to those seen in fast wind. Our results suggest that the Alfvénic slow wind has a different origin **from** the slow wind found near the boundary of coronal holes, where the amplitude of the Alfvénic fluctuations decreases together with decreasing the wind speed.

Keywords: Velocity Fields, Solar Wind; Magnetic fields, Interplanetary; Turbulence

1. Introduction

Solar wind fluctuations have been broadly studied (e.g. Goldstein, Roberts and Matthaeus, 1995; Tu and Marsch, 1995; Bruno and Carbone, 2013, and references

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therein). They are believed to play a fundamental role in different processes such as solar wind heating and acceleration, energetic particle acceleration, and cosmic-ray propagation.

The solar wind magnetic field and plasma parameters exhibit a high temporal and spatial variability. **They** covers time-scales spanning several years (of the order of the solar cycle) down to days (characteristic of the fast-slow stream structure) and hours and minutes (characteristic of solar wind turbulence). On a global scale, the relative fluctuations in magnetic field and **proton** density are $\sim$1, **as are** fluctuations in the radial speed between fast and slow streams. On the shorter, turbulent time-scales, the turbulent mach and alfvén numbers remain $\sim$1 suggesting that important information on the solar wind dynamics is carried by the fluctuating field.

When examining the correlations between the fluctuating quantities, a plethora of structures have been identified, including current sheets, magnetic holes, tangential and rotational discontinuities, pressure balanced structures as well as features resembling flux ropes or more isolated plasma blobs. However, spectral analysis reveals that these structures are embedded on what appears to be a magnetohydrodynamic (MHD) turbulent state, with power spectra in velocity, density and magnetic field fluctuations and anisotropies not far from contemporary theoretical predictions.

However, especially for plasma in fast solar wind streams coming from coronal holes (clearly visible open field regions on the Sun) one feature especially stands out: the Alfvénic character of fluctuations (e.g. Belcher and Davis, 1971; Belcher and Solodyna, 1975). Alfvénic fluctuations are characterized by a strong correlation between velocity and magnetic field fluctuations that correspond to large amplitude Alfvén waves always propagating away from the Sun (Belcher, Davis and Smith, 1969). In such periods, fluctuations in the **proton** density and in the magnitude of the magnetic field are remarkably depleated when compared, respectively, to the expectations from the turbulent mach number or from the magnitude of the magnetic field fluctuations themselves (Grappin, Velli and Mangeney, 1991). In other words, the fluctuations are non compressive, and the magnetic field vector wanders on a quasi-sphere whose radius is the magnetic field magnitude. Such fluctuations tend to dominate the lower frequency parts of the power spectrum, displaying an anomalous **frequency power law exponent of -1 (indicated as f^{-1})**, and the frequency extent decreases with increasing heliocentric distance from the Sun (Tu and Marsch, 1995). When strong velocity shears and compressive phenomena (corotating interaction regions, CMEs and shocks) are absent (Roberts *et al.*, 1987), for example in the polar wind seen at Ulysses, Alfvénic correlations survive up to very large distances from the Sun.

The Alfvénic turbulence seen in high speed streams typically has a larger relative amplitude than the more typical, compressible turbulence seen in slow streams: Ko *et al.* (2018) show that the transition between the higher and lower amplitude fluctuations **with** changing wind speed is rather abrupt, and the lowest fluctuation amplitudes correspond to the lowest speed in a solar wind stream.

On the other hand, a recent study by D'Amicis and Bruno (2015) performed at 1 AU showed that the slow solar wind is sometimes characterized by a high degree of Alfvénicity. This is quite surprising since the v-b correlation, **where v and b are velocity and magnetic field fluctuations**, is supposed to degrade with increasing heliocentric distance. D'Amicis, Matteini and Bruno (2019) further developed this study and suggested that a possible solar source for this Alfvénic slow solar wind could be identified in low-latitude small coronal holes (in agreement with Wang, 1994; Neugebauer *et al.*, 1998). The latter were found to be an ubiquitous feature of the solar surface during maximum of solar cycle 23 (Platten *et al.*, 2014). D'Amicis, Matteini and Bruno (2019) showed that the fast wind and the Alfvénic slow wind share several common characteristics, probably due to a similar solar origin. In the Alfvénic slow wind, a major role **could** be played by the super-radial expansion responsible for the lower velocity.

Moreover, D'Amicis, Matteini and Bruno (2019) found that the power associated **with** magnetic field fluctuations in the Alfvénic slow wind is comparable to that of the fast wind but larger than that found in the typical slow wind. The power in the field magnitude is typically an order of magnitude lower than that found in the components, due to a low level of compressive fluctuations (Bavassano *et al.*, 1982). In high-speed streams, the amplitude of magnetic field fluctuations are generally high (typically, $\delta B/B \sim 1$, **where δB is the amplitude of the fluctuations and B is the intensity of the backgound magnetic field**) with high levels of v-b correlation coefficient, indicating the dominance of outward propagating Alfvénic fluctuations on a wide range of scales (e.g. Marsch and Tu, 1990). It can be noticed that the amplitude of the magnetic field fluctuations components depends on the scale: $\delta B \sim B$ at the largest scale while $\delta B \ll B$ at smaller scales. These features along with a constant B characterize Alfvénic fluctuations. This can be easily pictured as the tip of the magnetic field vector constrained to move on a sphere of approximately constant radius (almost constant B magnitude), as observed by Bruno *et al.* (2004) and Matteini *et al.* (2015). Matteini *et al.* (2018) found also that the low-magnetic compressibility determines a well-defined limit for the amplitude of the fluctuations. Actually, the maximum amplitude δB of the difference between two magnetic field measurements is twice the radius of the sphere, i.e., $\delta B \leq 2B$. Bruno *et al.* (2019) found that the same limitation is still valid for the slow wind provided that directional fluctuations are much larger than the compressive ones.

Typical power density spectra are characterized by at least three different frequency ranges. At the lowest frequencies, in some cases an f^{-1} regime is observed corresponding to fluctuations of the large scales containing energy (Matthaeus and Goldstein, 1986; Dmitruk and Matthaeus, 2007; Matteini *et al.*, 2018). The f^{-1} regime is separated by a spectral break from a typical turbulence spectrum, as first shown by Coleman (1968), which is generally characterized by a Kolmogorov scaling of $f^{-5/3}$. Around the proton scales, kinetic effects alter the cascade which leads to steeper spectra into the dissipation region. In a recent study, D'Amicis, Matteini and Bruno (2019) showed power spectra (of the trace) of magnetic field fluctuations for different solar wind regimes and found that the power associated **with** magnetic field fluctuations in the Alfvénic solar wind is comparable to that in the fast wind and it is higher than in the slow wind. The reason for this being the presence of large amplitude Alfvénic fluctuations. At higher frequencies, right beyond the spectral break, the same study shows a clear relationship between the slope of the spectrum in the sub-ion range and the power of the fluctuations in the inertial range, in agreement with Bruno and Trenchi (2013).

Due to the high degree of correlation between magnetic and velocity fluctuations, we expect that the two vectors behave in a similar way. Consistent with that, a visual inspection of the time series of the speed profile reveals that the Alfvénic slow wind is characterized by larger fluctuations with respect to the typical slow wind. Properties of velocity fluctuations and their comparison with magnetic ones have been studied in the literature for large dataset (e.g. Borovsky, 2012). One of the well-established results is the different spectral slope characterizing the turbulent inertial range, close **to a frequency power-law exponent** of $-5/3$ for the magnetic field and o $-3/2$ for the velocity (e.g. Bruno and Carbone, 2013). **Velocity power spectra show power-law exponents often with values near the Iroshnikov-Kraichnan scaling of 3/2 rather than the Kolmogorov scaling of 5/3 (Salem, 2000; Podesta, Roberts and Goldstein, 2006, 2007; Salem *et al.*, 2009; Borovsky, 2012)**. However, as remarked by Roberts (2010), Voyager observations have showed that the power spectrum of velocity fluctuations evolves with the heliocentric distance and steepens toward a Kolmogorov scaling well past 1 AU, matching the magnetic spectrum behaviour and the theoretical expectation of the Kolmogorov theory.

In this work we extend the comparison between magnetic and velocity fluctuations specifically for fast and slow Alfvénic periods, by investigating the amplitude and spectral properties of the fluctuations.

2. Data analysis

This work is based on the analysis of case studies describing the behaviour of the amplitude of magnetic field and velocity fluctuations of different types of solar wind, i.e. fast wind, typical slow wind and Alfvénic slow solar wind. Plasma data are derived from the Three-Dimensional Plasma and Energetic Particle Investigation (3DP) and magnetic field data from the Magnetic Field Investigation (MFI) both on board **Wind** at 24 s resolution when the spacecraft was in the solar wind. We focus on two time intervals:

- day 1-11 of year 1995 selected during minimum of solar activity and **containing** a fast wind stream
- day 350-360 of year 2000 selected during maximum of solar activity containing a portion of typical slow wind along with an interval of Alfvénic slow wind.

These intervals are not isolated cases but rather representative examples of the solar wind regime selected.

In Figure 1, we show summary plots of the two intervals days 1-11 of year 1995 (left panels) and days 350-360 of year 2000 (right panels): from top to bottom, the time series of solar wind bulk speed (V_{sw}), the v-b correlation coefficient (C_{vb}) computed using a sliding window at 1 h scale, the z component of velocity (v_z) and magnetic field, b_z, in Alfvén units, v_{Az} (with $v_{Az} = b_z/\sqrt{4\pi\rho}$ and ρ the

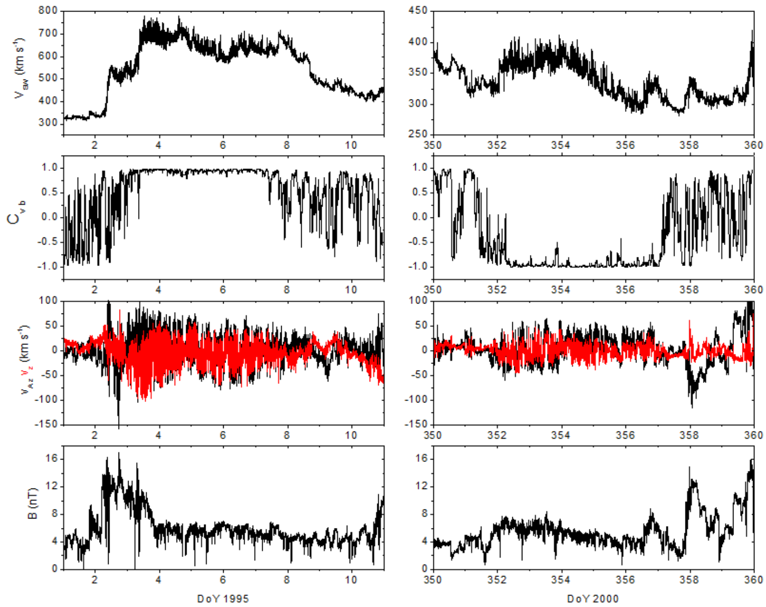

Figure 1. Summary plots for the time intervals extending from day 1 to 11 of year 1995 (solar minimum, left panels) and from day 350 to 360 of year 2000 (solar maximum, right panels): (from top to bottom) time series of solar wind bulk speed (V_{sw}), v-b correlation coefficient computed at 1 h scale (C_{vb}), (red) the z component of velocity (v_z) and (black) the z component of the magnetic field in Alfvén units (v_{Az}) in GSE, magnetic field magnitude (B).

mass density) **in GSE coordinate system**, magnetic field magnitude (B). C_{vb} is a measure of the degree of Alfvénicity. The time series of v_z and v_{Az} allow also to compare the amplitude of fluctuation which is found be larger during Alfvénic intervals than in non-Alfvénic periods.

In particular, the left side of Figure 1 shows a typical fast wind stream in which we can easily identify:

- a compression region (from around day 2 to 4) which is a result of the interaction between fast and slow solar wind, thus marking the transition between slow and fast speed wind;
- the main portion of the stream (from day 4 to 8) characterized by high speed and large amplitude fluctuations;
- a rarefaction region (from day 8 to 11) where velocity decreases and fluctuations have a smaller amplitude.

The three regions are characterized by different v-b correlation coefficients. The strong compression region ahead of the main portion of the stream is characterized by an **increase in magnetic field intensity and a b_z component in Alfvén units** larger than, and completely unrelated to, the corresponding v_z component. This is why C_{vb} oscillates and on average has small values thus showing its non-Alfvénic behaviour. This happens **over the whole** interval except for the main portion of the stream where C_{vb} is very high, on average around 0.95. On the other hand it can also be noted that the amplitude of the fluctuations varies **throughout** the time interval, being larger in the main portion of the fast stream.

On the other hand, the right side of Figure 1 shows a representative case study displaying Alfvénic slow solar wind with a typical slow wind preceding it. The Alfvénic slow wind displays a speed profile very similar to that of the fast wind. Actually, it is characterized by a faster main portion of the stream, followed by a small time interval that could be seen as a kind of rarefaction region with a slower velocity. This is a feature found in other cases during the same solar maximum as already mentioned by D'Amicis, Matteini and Bruno (2019). For this interval we notice the same variation in the v-b correlation coefficient, with very high values (around 0.94) from around day 352.5 to 357. Even in this case the amplitude of the fluctuations is larger in the Alfvénic slow wind rather than in the typical slow wind preceding it. The end of the interval corresponds to magnetic field compression so that the magnetic field component is larger than that of velocity and it is completely unrelated to it thus it turns to be non-Alfvénic with C_{vb} oscillating and on average having small values.

Finally, note that for both regimes, in the main part of the stream when the amplitude of the fluctuations is the largest, the magnetic field intensity (bottom panel) remains relatively stable; this is a consequence of the Alfvénicity of the fluctuations and the low level of B variations associated to it.

Moreover, the Alfvénic slow wind has an average bulk speed comparable to that of the typical slow wind. However, as shown in Figure 1, it is characterized by large fluctuations in both velocity and magnetic field components. This concerns also the radial components of the fields, so that the Alfvénic slow wind speed profile displays significant fluctuations as typically observed in the fast wind (Matteini *et al.*, 2014) and larger with respect to periods of low Alfvénic correlations. These features, together with a remarkably low plasma and magnetic compressibility (almost constant magnetic field magnitude and number density, not shown here), all suggest a clear similarity between the fluctuations in the Alfvénic slow and fast wind.

3. Magnetic field fluctuations

To explore further this similarity, we address now spectral properties of the fluctuations. We compute the power spectral density of the trace of magnetic field fluctuations to focus on the amplitude of the fluctuations. We selected data at 3 s resolution, available for both plasma and magnetic field. This is the time sampling of plasma moments computed on board. Although they exhibit quantization at the shortest time scale, this resolution allows better statistics while not influencing lower frequency power spectral density. Spectra for the three typical regimes are shown in the left panel of Figure 2: as discussed in D'Amicis, Matteini and Bruno (2019), Alfvénic slow and fast wind display similar power, much larger than the non-Alfvénic slow wind. We then normalized the power spectra to allow comparison between different solar wind types in the

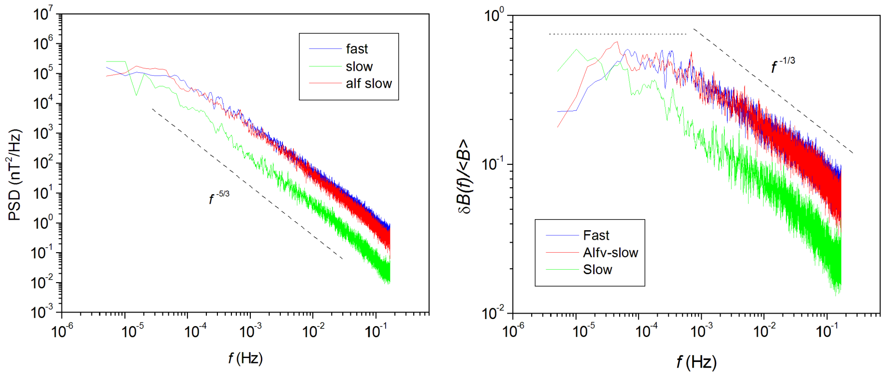

Figure 2. (Left) Power Spectral Density (PSD) of the trace of magnetic field components. The dashed line corresponds to the $f^{-5/3}$ scaling while the dotted line to the f^{-1}. (Right) Normalized power spectra of the trace of magnetic field fluctuations δB(f)/$\langle B \rangle$ for the solar wind regimes under study. The dashed line corresponds to the $f^{-1/3}$ scaling while the dotted horizontal line has been inserted to guide the eye. See explanation in text.

following way similar to Bruno *et al.* (2019). First, we derived the amplitude of the fluctuation $\delta B(f)$ at a given frequency from a relationship linking $\delta B(f)$ and the Fourier power spectral density, $P_B(f)$: $\delta B(f) = \sqrt{2fP_B(f)}$. These values were then normalized to the corresponding local magnetic field intensity average within each interval, $\langle B \rangle$. Figure 2 shows the normalized spectra obtained as explained above. Note that according to this normalization, we expect an inertial range characterized by a scaling of $f^{-1/3}$ since, if $\mathrm{P}_B(f) \sim f^{-5/3}$ (Kolmogorov scaling), then $\delta B(f) \sim f^{-1/3}$, represented by the dashed line. We also observe a flattening at low frequency range where the power density spectra shows the $1/f$ scaling corresponding in the normalized spectra, **shown as** an horizontal dotted line, indicating that the amplitude of the Fourier modes has saturated as discussed in Matteini *et al.* (2018); Bruno *et al.* (2019). In this worth noting that the power associated **with** magnetic field fluctuations in the slow wind is much lower than in the fast and Alfvénic slow solar wind. In addition no flattening is observed in this case at low frequencies, i.e., the spectrum displays a single $-5/3$ slope at all scales considered, with no $1/f$ range.

Another approach is to use the increments **of the field vector**, $\delta\mathbf{B}$, as done by Matteini *et al.* (2018) to study the amplitude of the fluctuations at a given scale. $\delta\mathbf{B}$ is defined as:

$$\delta\mathbf{B} = \mathbf{B}(t) - \mathbf{B}(t+\tau) \tag{1}$$

where $\mathbf{B}$ is the magnetic field vector and τ is assumed to be 3 h, which is a typical scale **within the** f^{-1} **regime** where saturation of the amplitude of fluctuations is observed (Bruno *et al.*, 2019). $\delta\mathbf{B}$ is then normalized to the average of the magnetic field magnitude, $\langle B \rangle$, computed over the time window τ. Figure 3 shows the histograms of $|\delta\mathbf{B}|/\langle B \rangle$ for fast and Alfvénic slow solar wind, respectively.

We computed the $|\delta\mathbf{B}|/\langle B \rangle$ amplitude for the two Alfvénic winds, finding that the distribution of $|\delta\mathbf{B}|/\langle B \rangle$ is centered around $\sim$1 for both fast and Alfvénic slow while it is lower for the slow wind (approximatively 0.5, not shown here).

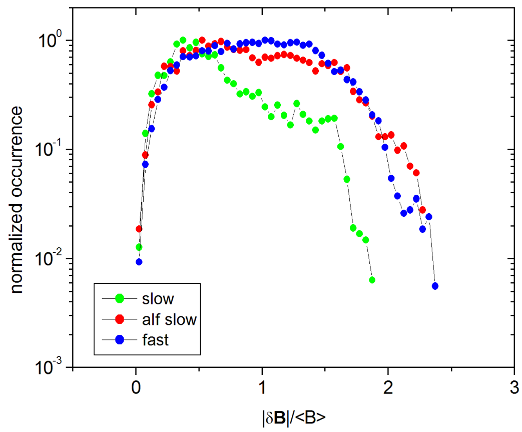

Figure 3. Histograms of the amplitude of the magnetic field fluctuations $|\delta \mathbf{B}|/\langle B\rangle$ at the scale $\tau = 3$ hr for fast wind (blue circles), typical slow (green circles) and Alfvénic slow wind (red circles).

This is another way to stress that the normalized amplitude of the fluctuations in the Alfvénic slow wind is comparable to that of the fast wind. Moreover, in both cases, the normalized amplitude is bounded between [0,2], as expected for fluctuations polarized on a sphere of constant radius B. To quantify further the amplitude of the fluctuations, we computed also the normalized variance, σ_z/B, for the different solar wind regimes. We found that it is about 0.5 for Alfvénic slow and fast wind (thus consistent with the fast wind stream shown in Tsurutani, Echer and Gonzalez, 2011, taking into account the square value) while it is only about 0.35 for the slow wind, as expected. Similar values are also obtained taking group averages over different time intervals of the same solar wind regimes.

4. Velocity fluctuations

We then computed the power spectral density of the trace of velocity fluctuations using data at 3 s resolution. The resulting spectra are shown in the left panel of Figure 4; **as** for the magnetic field, both Alfvénic slow and fast regimes have the largest power, although not exactly **at** the same level. From the spectra we derived the amplitude of each Fourier mode at a given frequency, as in previous section. These have been normalized to the corresponding average bulk speed, as shown in right panel; this is to highlight that despite similar bulk speed in the slow winds, the Alfvénic one has a $\delta V(f)/\langle V_{sw}\rangle$ ratio very similar to the fast wind. We recall that in this case, according to the normalization, we expect an inertial range characterized by a scaling of $f^{-1/4}$ since, if $P_V(f) \sim f^{-3/2}$ (Kraichnan scaling), then $\delta V(f) \sim f^{-1/4}$, indicated by the dashed line. We also observe a flattening at low frequency range where the power density spectra shows the $1/f$ scaling corresponding to the normalized spectra, shown by an horizontal dotted line. This suggests that the amplitude of the Fourier modes has saturated for the velocity counterpart too, as also discussed in Bruno *et al.* (2019) for the fast wind. Moreover, the power associated with velocity fluctuations in the slow wind is much lower than in the fast and Alfvénic slow solar wind and no flattening is observed in this case at low frequencies.

As in the previous section, we can also introduce velocity increments:

$$\delta\mathbf{V} = \mathbf{V}(t) - \mathbf{V}(t+\tau) \tag{2}$$

where $\mathbf{V}$ is the velocity vector and τ is 3 hr, similar to the magnetic field case. The left panel of Figure 5 shows the histograms of $|\delta\mathbf{V}|$ normalized to the average of Alfvén speed, v_A, in order to make a direct connection with the magnetic fluctuations. Clearly, the largest fluctuations in units of v_A are seen during the most Alfvénic periods. However, in both fast and Alfvénic slow solar wind the shape of the normalized velocity histograms are somehow different with respect to Figure 3. In particular the velocity fluctuations, once normalized to v_A, seem to have a lower amplitude compared to $\delta\mathbf{B}/\langle B\rangle$. This is a consequence of the coupling between magnetic and velocity fluctuations, and namely the ratio between $\delta B/B$ and δV. At 1 AU this typically deviates from the nominal Alfvén speed v_A due to the presence of some residual energy, the excess of magnetic energy with respect to the kinetic counterpart (Chen et al., 2013). As a consequence, the effective phase-velocity, v_ϕ, of the fluctuations can be instead inferred from the empirical δB-δV correlation (e.g. Goldstein *et al.*, 1996; Matteini *et al.*, 2015), and directly related to the so called Alfvén ratio r_A between the kinetic and magnetic energies of the fluctuations. **Indeed, v_ϕ is not simply equal to v_A rather to** $v_A\sqrt{r_A}$. In the present study, the slope of the δB-δV scatter plot, when δB and δV are normalized to B and v_A, is 0.71 and 0.63 for fast and Alfvénic slow solar wind, respectively. These values corresponds to $r_A < 1$ as expected. Since v_A for the two time intervals is 67 and 46 km s^{-1}, respectively, we derive v_ϕ as 48 and 29 km s^{-1} for fast and Alfvénic slow wind, respectively. As a consequence, to recover the underlying connection between δB and δV, fluctuations need to be normalized using v_ϕ, as this is the physical velocity coupling the two fields.

The right panel of Figure 5 then shows the histograms of $\delta\mathbf{V}/\langle v_\phi\rangle$ for fast and Alfvénic slow wind. It is not possible to define v_ϕ for the non-Alfvénic wind, due to the lack of δB-δV correlation. As expected, in this case the correspondence between magnetic and velocity normalized amplitudes is well captured, and the histograms for fast and Alfvénic slow solar wind collapse on top of each other, as it was the case for the magnetic field fluctuations.

5. Summary and conclusions

This paper shows a comparative study focusing on the behavior of different solar wind regimes with regard to the amplitude of magnetic field and velocity fluctuations.

We first performed a spectral analysis showing that the fast wind and the Alfvénic slow wind are characterized by higher power of the fluctuations than that of the typical slow wind. This indicates the presence of larger magnetic

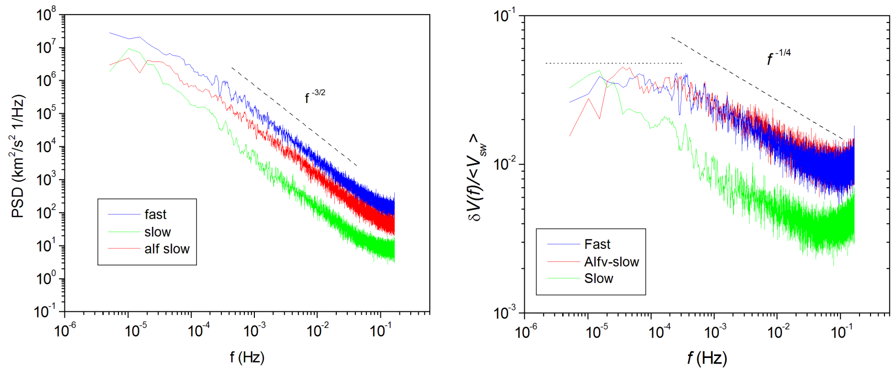

Figure 4. Power Spectral Density (PSD) of the trace of velocity components. The dashed line corresponds to the $f^{-3/2}$ scaling while the dotted line to the f^{-1}. (Right) Normalized power spectra of the velocity fluctuations $\delta V(f)/\langle V_{sw}\rangle$ for the solar wind regimes under study. The dashed line corresponds to the $f^{-1/4}$ scaling while the dotted horizontal line has been inserted to guide the eye. See explanation in text.

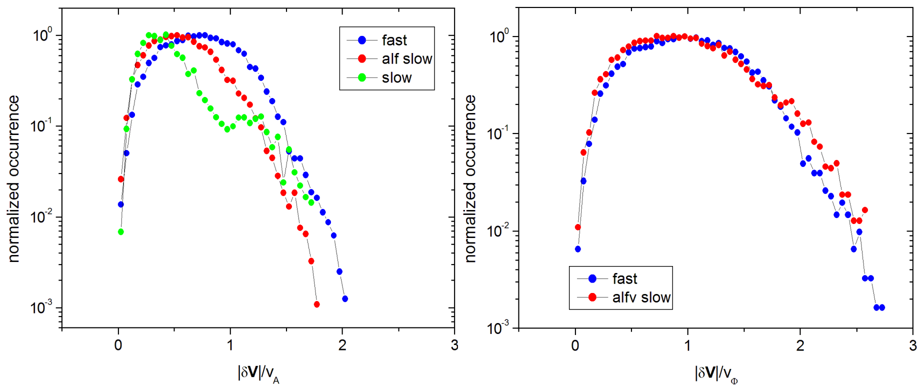

Figure 5. Histograms of the amplitude of the velocity fluctuations $|\delta\mathbf{V}|$ normalized to average of v_A (left) and v_ϕ (right), respectively, computed for $\tau = 3$ hr for fast wind (blue circles), typical slow (green circles) and Alfvénic slow wind (red circles).

field fluctuations in the two Alfvénic winds. The latter two show also an f^{-1} regime at low frequencies and a Kolmogorov scaling at higher frequencies. The typical slow wind, on the contrary, is generally characterized by a Kolmogorov scaling extending in the whole frequency range. Moreover, the relative amplitude of magnetic field fluctuations in the fast and in the Alfvénic slow solar wind is similar and higher than in the slow solar wind.

The same analysis was performed on velocity fluctuations. In this case, the comparison between standard power spectra and normalized ones is meaningful. Indeed, standard power spectra shows that the largest amplitudes correspond to the fast wind and the smallest to typical slow wind, while the Alfvénic slow is **somewhere** in between. When comparing the relative amplitude of the fluctuations **with** respect to the bulk speed, the two Alfvénic winds show similar relative amplitudes, larger than those of the typical slow wind.

Overall, in fast and Alfvénic slow solar wind, power spectra are characterized by a break in the spectrum and a $1/f$ range at large scales. We have shown that in the $1/f$ range of highly Alfvénic fast wind intervals, velocity fluctuations display a saturation of the amplitude and, like the magnetic field (Matteini *et al.*, 2018), they are roughly bounded between 0 and $2v_A$. Interestingly, the same dynamics is recovered for the slow Alfvénic wind, provided that one normalizes velocity fluctuations to the effective phase velocity v_ϕ inferred by the local δB-δV correlation. When this is done, the magnetic and velocity PDFs of the fluctuations coincide, consistent with the presence of a $1/f$ range at large scales for both fields. The very close behavior in the properties of magnetic and velocity fluctuations is a direct consequence of the Alfvénic nature of the fluctuations. By contrast, when a 1/f range is observed in the magnetic spectrum of long enough intervals of non-Alfvénic slow wind (Bruno *et al.*, 2019), the velocity never shows a similar scaling since magnetic and velocity fluctuations are decoupled.

The present study confirms preliminary results by D'Amicis, Matteini and Bruno (2019) and highlights that the Alfvénic slow solar wind during the maximum of activity of the solar cycle is characterized by large amplitude fluctuations as well as a high Alfvénicity.

However, these results seem not to match the observations typically performed at the boundary of coronal holes, where both the Alfvénicity and the amplitude of the fluctuations lower with decreasing speed (e.g. Tsurutani, Echer and Gonzalez, 2011). This would suggest a different scenario for the origin of the Alfvénic slow solar wind regime observed here. Within this framework, the Parker Solar Probe (PSP) mission launched in August 2018 and the upcoming Solar Orbiter mission to be launched in February 2020 will shed light on this topic, sampling the solar wind over the upcoming solar cycle: by measuring solar wind streams inside the Alfvén surface, PSP should allow a better understanding of the correlations between wind speed and Alfvénicity, and therefore elucidate the relative role of fluctuations in accelerating and heating the wind. The combined in-situ and remote sensing observations from Solar Orbiter should help, in conjunction with PSP, to pinpoint the source regions of the different **solar wind** types with an accuracy of a supergranule or less ($\sim$ 25 Mm on the Sun). We predict that these measurements, in the more pristine source regions of the wind, will show even greater variability in the association between turbulence and wind speed than observed here, and allow a dynamical understanding of their origin.

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References

Bavassano, B., Dobrowolny, M., Mariani, F., Ness, N.F.: 1982, Radial evolution of power spectra of interplantary Alfvénic turbulence. *J. Geophys. Res.* **87**, 3617. DOI: 10.1029/JA087iA05p03617.

Belcher, J.W., Davis, L. Jr., Smith, E.J.: 1969, Large-amplitude Alfvén waves in the interplanetary medium: Mariner 5. *J. Geophys. Res.* **74**, 2302. DOI: 10.1029/JA074i009p02302.

Belcher, J.W., Davis, L.: 1971, Large-amplitude Alfvén waves in the interplanetary medium, 2. *J. Geophys. Res.* **76**, 3534. DOI: 10.1029/JA076i016p03534.

Belcher, J.W., Solodyna, C.V.: 1975, Alfvén waves and directional discontinuities in the interplanetary medium. *J. Geophys. Res.* **80**, 181. DOI: 10.1029/JA080i001p00181.

Borovsky, J.E.: 2012, The velocity and magnetic field fluctuations of the solar wind at 1 AU: Statistical analysis of Fourier spectra and correlations with plasma properties. *J. Geophys. Res.* **117**, A05104. DOI: 10.1029/2011JA017499.

Bruno, R., Carbone, V., Primavera, L., Malara, F., Sorriso-Valvo, L., Bavassano, B., Veltri, P.: 2004, On the probability distribution function of small-scale interplanetary magnetic field fluctuations. *Ann. Geophys.* **22**, 375. DOI: 10.5194/angeo-22-3751-2004.

Bruno, R., Carbone, V.: 2013, The Solar Wind as a Turbulence Laboratory. *Living Rev. Sol. Phys.* **10**, 2. DOI: 10.12942/lrsp-2013-2.

Bruno, R., Trenchi, L.: 2014, Radial Dependence of the Frequency Break between Fluid and Kinetic Scales in the Solar Wind Fluctuations. *Astrophys. J.* **787**, L24. DOI: 10.1088/2041-8205/787/2/L24.

Bruno, R., Telloni, D., Sorriso-Valvo, L., Marino, R., De Marco, R., D'Amicis, R.: 2019, On the low-frequency break observed in the slow solar wind magnetic spectra. *A&A* **627**, A96. DOI: 10.1051/0004-6361/201935841.

Camporeale, E., Caré, A., Borovsky, J.E.: 2017, Classification of Solar Wind With Machine Learning. *J. Geophys. Res.* **122**, 10910. DOI: 10.1002/2017JA024383.

Chen C. H. K., Bale S. D., Salem C. S., Maruca B. A.: 2013, Residual Energy Spectrum of Solar Wind Turbulence. *Astrophys. J.*, **770**, 125. DOI: 10.1088/0004-637X/770/2/125.

Coleman, P.J.: 1968, Turbulence, Viscosity, and Dissipation in the Solar-Wind Plasma. *Astrophys. J.* **153**, 371. DOI: 10.1086/149674.

D'Amicis, R., Bruno, R.: 2015, On the Origin of Highly Alfvénic Slow Solar Wind. *Astrophys. J.* **805**, 84. DOI: 10.1088/0004-637X/805/1/84.

D'Amicis, R., Bruno, R., Matteini, L.: 2016, Characterizing the Alfvénic slow wind: A case study. Proceedings of the 14th Solar Wind Conference, AIP Conference Proceedings, edited by L. H. Wang, R. Bruno, E. Moebius, A. Vourlidas, and G. Zank (American Institute of Physics, Melville, NY, 2016). DOI: 10.1063/1.4943813.

D'Amicis, R., Matteini, L., Bruno, R.: 2019, On the slow solar wind with high Alfvénicity: from composition and microphysics to spectral properties. *MNRAS* **483**, 4665. DOI: 10.1093/mnras/sty3329.

Dmitruk, P., Matthaeus, W.H.: 2007, Low-frequency 1/f fluctuations in hydrodynamic and magnetohydrodynamic turbulence. *Phys. Rev. E* **76**, 036305. DOI: 10.1103/PhysRevE.76.036305.

Goldstein, M.L., Roberts, D.A., Matthaeus, W.H.: 1995, Magnetohydrodynamic turbulence in the solar wind. *Annual Review of Astronomy and Astrophysics* **33**, 283. DOI: 10.1146/annurev.aa.33.090195.001435.

Goldstein, B. E., et al.: 1996, Ulysses plasma parameters: Latitudinal, radial, and temporal variations. *A&A*, **316**, 296.

Grappin, R., Velli, M., Mangeney, A.: 1991, "Alfvénic" versus "standard" turbulence in the solar wind. *Ann. Geophys.* **9**, 416.

Horbury, T.S., Balogh, A.: 2001, Evolution of magnetic field fluctuations in high-speed solar wind streams: Ulysses and Helios observations. *J. Geophys. Res.* **106**, 15929. DOI: 10.1029/2000JA000108.

Ko, Y.-K., Roberts, D.A., Lepri, S.T.: 2018, Boundary of the Slow Solar Wind. *Astrophys. J.* **864**, 139. DOI: 10.3847/1538-4357/aad69e.

Marsch, E., Tu, C.-Y.: 1990, On the radial evolution of MHD turbulence in the inner heliosphere. *J. Geophys. Res.* **95**, 8211. DOI: 10.1029/JA095iA06p08211.

Matteini, L., Horbury, T.S., Neugebauer, M., Goldstein, B.E.: 2014, Dependence of solar wind speed on the local magnetic field orientation: Role of Alfvénic fluctuations. *Geophys. Res. Lett.*, **41**, 259. DOI: 10.1002/2013GL058482.

Matteini, L., Horbury, T.S., Pantellini, F., Velli, M., Schwartz, S.J.: 2015, Ion Kinetic Energy Conservation and Magnetic Field Strength Constancy in Multi-fluid Solar Wind Alfvénic Turbulence. *Astrophys. J.* **802**, 11. DOI: 10.1088/0004-637X/802/1/11.

Matteini, L., Stansby, D., Horbury, T.S., Chen, C.H.K.: 2018, On the 1/f Spectrum in the Solar Wind and Its Connection with Magnetic Compressibility. *Astrophys. J. Lett.* **869**, L32. DOI: 10.3847/2041-8213/aaf573.

Matthaeus, W.H., Goldstein, M.L.: 1986, Low-Frequency 1/f Noise in the Interplanetary Magnetic Field. Phys. Rev. Lett., 57, 495. DOI: 10.1103/PhysRevLett.57.495.

Neugebauer, M., Forsyth, R.J., Galvin, A.B., Harvey, K.L., Hoeksema, J.T., Lazarus, A.J., et al.: 1998, Spatial structure of the solar wind and comparisons with solar data and models. *J. Geophys. Res.* **103**, 14587. DOI: 10.1029/98JA00798 .

Platten, S. J., Parnell, C. E., Haynes, A. L., et al. 2014, The solar cycle variation of topological structures in the global solar corona. A&A, 565, A44. DOI: 10.1051/0004-6361/201323048.

Podesta, J.J., Roberts, D.A., Goldstein, M.L.: 2006, Power spectrum of smallscale turbulent velocity fluctuations in the solar wind. *J. Geophys. Res.* **111**, A10109. DOI: 10.1029/2006JA011834.

Podesta, J.J., Roberts, D.A., Goldstein, M.L.: 2007, Spectral exponents of kinetic and magnetic energy spectra in solar wind turbulence. *Astrophys. J.*, **664**, 543. DOI: 10.1086/519211.

Roberts, D.A., Klein, L.W., Goldstein, M.L., Matthaeus, W.H.: 1987, The nature and evolution of magnetohydrodynamic fluctuations in the solar wind - Voyager observations. *J. Geophys. Res.* **92**, 11021. DOI: 10.1029/JA092iA10p11021.

Roberts, D.A.: 2010, Evolution of the spectrum of solar wind velocity fluctuations from 0.3 to 5 AU. *J. Geophys. Res.* **105**, A12101. DOI: 10.1029/2009JA015120.

Salem, C.: 2000, PhD thesis, Univ. Paris VII.

Salem, C., Mangeney, A., Bale, S.D., Veltri, P.: 2009, Solar wind magnetohydrodynamics turbulence: anomalous scaling and role of intermittency. *Astrophys. J.*, **702**, 537. DOI: 10.1088/0004-637X/702/1/537.

Tsurutani, B.T., Echer, E., Gonzalez, W.D.: 2011, The solar and interplanetary causes of the recent minimum in geomagnetic activity (MGA23): a combination of midlatitude small coronal holes, low IMF Bz variances, low solar wind speeds and low solar magnetic fields. *Ann. Geophys.* **29** Ann. Geophys., 29, 839. DOI: 10.5194/angeo-29-839-2011.

Tsurutani, B.T., Lakhina, G.S., Sen, A., Hellinger, P., Glassmeier, K.-H., Mannucci, A.J.: 2018, A Review of Alfvénic Turbulence in HighSpeed Solar Wind Streams: Hints From Cometary Plasma Turbulence. *J. Geophys. Res.* **123**, 2458. DOI: 10.1002/2017JA024203.

Tu, C.-Y., Marsch, E.: 1995, MHD structures, waves and turbulence in the solar wind: Observations and theories. *Space Sci. Rev.* **73**, 1. DOI: 10.1007/BF00748891.

Wang, Y.-M.: 1994, Two types of slow solar wind. *Astrophys. J. Lett.* **437**, L67. DOI: 10.1086/187684.