Coherent Structures at Ion Scales in Fast Solar Wind: Cluster Observations

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Abstract

We investigate the nature of magnetic turbulent fluctuations, around ion characteristic scales, in a fast solar wind stream, by using Cluster data. Contrarily to slow solar wind, where both Alfvénic (\(\delta b_A \gg \delta b_b\)) and compressive (\(\delta b_B \gg \delta b_b\)) coherent structures are observed, the turbulent cascade of fast solar wind is dominated by Alfvénic structures, namely, Alfvén vortices, with a small and/or finite compressive part, with the presence also of several current sheets aligned with the local magnetic field. Several examples of vortex chains are also recognized. Although an increase of magnetic compressibility around ion scales is observed also for fast solar wind, no strongly compressive structures are found, meaning that the nature of the slow and fast winds is intrinsically different. Multispacecraft analysis applied to this interval of fast wind indicates that the coherent structures are almost convected by the flow and aligned with the local magnetic field, i.e., their normal is perpendicular to \(B\), which is consistent with a two-dimensional turbulence picture. Understanding intermittency and the related generation of coherent structures could provide a key insight into the nonlinear energy transfer and dissipation processes in magnetized and collisionless plasmas.

Key words: plasmas – solar wind – turbulence

1. Introduction

Turbulence is a complex, fascinating, and highly nonlinear process ubiquitous in nature. The dynamical evolution of a turbulent system is a consequence of the nonlinearity responsible for the coupling of many degrees of freedom, which leads the system far from thermal equilibrium. In typical hydrodynamic systems, the energy, injected at large scales, is transferred self-consistently toward smaller scales, where it finally can be dissipated (Kolmogorov 1941). Moreover, the turbulent activity becomes more and more inhomogeneous and nonuniform as the energy arrives to smaller and smaller scales. This phenomenon, named intermittency (Frisch 1995), is due to the presence of coherent structures, i.e., filaments of the vorticity field localized in space but covering scales from about the integral scale to the dissipation scale and with a characteristic tube-like structure (She et al. 1990; Frisch 1995). These intermittent contain most of the energy of the flow. Although for classical fluids the turbulence is fairly well understood, in plasma physics this process represents one of the most spectacular and unsolved problems, where both cross-scale couplings and kinetic effects are present. In this case, indeed, the energy, injected at large scales, progressively decays toward smaller scales, where kinetic effects (heating, particle acceleration, and so on) dominate the plasma dynamics.

Thanks to the support of many space missions, we have the unique opportunity to analyze directly the dynamics of a natural turbulent plasma: the solar wind, a continuous but highly variable, weakly collisional, and multicomponent plasma outflow from the Sun that travels at high speed. “In situ” measurements generally show that the interplanetary medium is in a state of fully developed turbulence, characterized by a multiscale nonlinear behavior (Bruno & Carbone 2013). In the inertial range the turbulent magnetic field cascade manifests a power law similar to the fluid behavior (Kolmogorov 1941). However, around ion characteristic scales, a change in the spectral shape is observed, with the presence of a steeper spectrum (Leamon et al. 1998, 2000; Bale et al. 2005; Smith et al. 2006; Alexandrova et al. 2007, 2008; Bourouaine et al. 2012; Bruno et al. 2014; Lion et al. 2016) and an increase of the magnetic compressibility (Alexandrova et al. 2007, 2008; Hamilton et al. 2008; Salem et al. 2012; Kiyani et al. 2013; Telloni et al. 2015; Lacombe et al. 2017). In this frequency range, often called the dissipation range, the plasma dynamics is governed by kinetic effects, namely, strong anisotropies in the ion velocity distributions, with preferential perpendicular heating and parallel accelerated particles with respect to the background magnetic field. At scales smaller than the ion characteristic scales and up to a fraction of the characteristic electron lengths, another general spectrum is observed, whose interpretation is still controversial (Alexandrova et al. 2009, 2012; Sahraoui et al. 2010, 2013).

A very important aspect of the solar wind turbulent cascade is intermittency, due to the non-Gaussian and bursty nature of the turbulent fluctuations, with the non-Gaussianity that increases toward smaller scales. Therefore, as in the fluid case, also in the solar wind the energy is not uniformly distributed in space (Bruno et al. 2001), but is localized in coherent structures, i.e., structures characterized by a phase synchronization among a certain number of scales. A clear link exists between intermittency, non-Gaussianity, and phase coherence. Koga et al. (2007) have shown, in the solar wind turbulence near Earth’s bow shock, that a similar behavior exists between the phase coherence index and the kurtosis (flatness), reflecting a departure from Gaussianity of the probability density function of the magnetic field fluctuations, where the non-Gaussianity of the fluctuations is a clear signature of intermittency.

In recent decades, the presence of planar structures, such as current sheets, rotational discontinuities, and shocks (Veltri 1999; Veltri & Mangeney 1999; Salem et al. 2009; Greco et al. 2012; Perri et al. 2012; Greco & Perri 2014), was considered to be the principal cause of intermittency in solar...
wind at ion scales. Recent studies have shown that other types of coherent structures also contribute to the intermittency phenomenon in the solar wind turbulence. Lion et al. (2016) have shown the presence of Alfvénic vortex-like structures in a fast solar wind stream by using wind measurements. Moreover, a study by Roberts et al. (2016) using multisatellite measurement from Cluster spacecraft has shown a well-defined Alfvén vortex in a slow solar wind stream. These structures occur close to ion characteristic scales, similar to what happens to the vortices observed in Earth’s and Saturn’s magnetosheaths (Alexandrova et al. 2006; Alexandrova & Saur 2008).

More recently, a statistical analysis of coherent structures around ion scales in a slow solar wind stream has been performed by Perrone et al. (2016), using Cluster measurements. This study has shown, for the first time, that different families of coherent structures participate in the intermittency at ion scales in slow solar wind, such as compressive structures, i.e., magnetic holes, solitons, and shocks, and Alfvénic structures in the form of current sheets and vortices. These last ones can have an important compressive part, and they are the most frequently observed during the analyzed interval. All the observed structures are field aligned with normals perpendicular to the local mean magnetic field, which is consistent with two-dimensional \((k_i \gg k_b)\) turbulence. Moreover, although most of the structures are merely advected by the wind, 25% of the analyzed structures propagate in the plasma reference frame.

Despite the fact that several studies have been performed to understand the complex behavior of the solar wind, the nature of the turbulent fluctuations around ion scales and the dissipation in such a collisionless medium still remain an open question. The purpose of the present paper is to shed light on the nature of the turbulent fluctuations around ion scales in fast solar wind by using multipoint measurements from Cluster spacecraft. The fast solar wind is generally characterized by a higher proton temperature and a lower density with respect to the slow solar wind. Other differences between the two streams are the composition, the Alfvénic content, and the anisotropies in ion and electron temperatures.

In the present work, first we focus on the turbulent character of the considered stream and on the phase coherence between the components of the magnetic field, by using wavelet analysis (Farge 1992; Torrence & Compo 1998). Wavelet transforms are a mathematical method, which allow unfolding a signal, or a field, into both time and scale at once. The wavelet analysis can be performed locally on the signal, as opposed to the Fourier transform, which is inherently nonlocal. By expanding the signal in a set of functions that are localized in time as well as in frequency, it is possible to highlight the presence of regions characterized by intermittency in the considered stream, thus studying the “texture” of the turbulence. Then, we investigate in detail the magnetic field fluctuations close to the ion scales by using the timing method for the analysis of multisatellite data (Schwartz 1998; Perrone et al. 2016). The considered interval of solar wind appears to be characterized by the presence of coherent structures. Moreover, by applying the multipoint signal resonator (MSR) technique (Narita et al. 2001, 2011) to the same magnetic fluctuations, we verify the applicability of the \(k\)-filtering in the case of strong turbulence, i.e., in the presence of coherent structures.

Finally, as a result of the statistical studies on the coherent structures observed in the stream, we find that the ion scales are dominated by Alfvén vortices, with a small and/or finite compressive part. Moreover, we observe the presence also of several current sheets aligned with the magnetic field, almost convected by the wind. The comparison of these results with the results presented in Perrone et al. (2016) suggests that the physics that governs the ion scales of fast and slow solar wind is quite different.

The paper is organized as follows. In Section 2 we describe the selected data interval of fast solar wind in terms of plasma parameters and turbulent behavior, and in Section 3 we discuss the concepts of intermittency and phase coherence. In Section 4 we present some examples of detected coherent structures and theoretical models in order to explain the observations. In Section 5 we determine spatial orientation and plasma frame velocities of the observed structures by using multisatellite analysis, and in Section 6 we summarize the results and discuss our conclusions. Finally, in the Appendix we present the results of the MSR technique.

2. Fast Solar Wind Interval

We consider an interval of about 40 minutes (17:30–18:10 UT) of undisturbed solar wind from Cluster spacecraft on 2004 January 31. It is a stream of fast solar wind, with a mean speed of about 600 km s\(^{-1}\), characterized by a mean magnetic field of \(\sim 8.3\) nT, a mean proton density of \(\sim 3–4\) cm\(^{-3}\), and a mean proton temperature of \(\sim 37\) eV, with \(T_{\parallel,p} \sim 30\) eV and \(T_{\perp,p} \sim 41\) eV. In terms of characteristic plasma scales, the proton Larmor radius, defined as the ratio between the perpendicular proton thermal speed and the proton cyclotron frequency, is \(\rho_p \sim 109\) km, while the proton inertial length, defined as the ratio between the light speed and the proton plasma frequency, is \(\lambda_p \sim 121\) km. Finally, the proton plasma beta, \(\beta_p\), defined as the ratio between proton kinetic pressure and magnetic pressure, has an averaged value in the interval of about 0.8, with several regions where \(\beta_p > 1\).

Although some caveats exist for the electron moments by using the Plasma Electron and Current Experiment (PEACE; Johnstone et al. 1997; Fazakerley et al. 2009), in this interval of fast solar wind the mean parallel and perpendicular temperatures are about \(T_{\parallel,e} \sim 18\) eV and \(T_{\perp,e} \sim 14\) eV, respectively. Therefore, the electron Larmor radius is \(\rho_e \sim 1.5\) km. By using the Waves of High Frequency and Sounder for Probing of the Electron Density by Relaxation (WHISPER) experiment (Décuëre et al. 2001), the electron density is known \((\sim 4\) cm\(^{-3}\)), with a resolution of 1.5 s, and the electron inertial length can be derived \((\lambda_e \sim 2.6\) km).

Figure 1 gives a brief overview of the considered interval from Cluster\(^1\). In particular, in panel (a) we show the three components of the velocity field from the Hot Ion Analyser (HIA) sensor of the Cluster Ion Spectrometry (CIS) with a resolution of 4 s (Rème et al. 2001). Here, \(x\) (black), \(y\) (red), and \(z\) (blue) denote the Geocentric Solar Ecliptic (GSE) coordinate system, i.e., the \(x\) component points toward the Sun and the \(z\) axis is perpendicular to the plane of Earth’s orbit around the Sun (positive north). The \(v_\gamma\), which is the component in the direction antiparallel to the direction of Earth’s motion, has been corrected for the \(\sim 30\) km s\(^{-1}\) aberration produced by the orbital speed of the spacecraft and Earth around the Sun. Moreover, panel (b) displays the raw data of the magnetic field vector, from the Fluxgate Magnetometer (FGM; Balogh et al. 2001), where the three components are also given in GSE, by using the same colors as

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The frequency dependence is easily obtained using the PSD of each component of the magnetic field and is defined as

\[ S_i(\tau) = \frac{2\delta t}{N} \sum_{j=0}^{N-1} |W_i(\tau, t_j)|^2, \quad i = x, y, z. \]  

Here \( \delta t \) is the time spacing and \( W_i \) are the Morlet wavelet coefficients for different timescales \( \tau \) and time \( t_j \) (Torrence & Compo 1998),

\[ W_i(\tau, t) = \sum_{j=0}^{N-1} B_j(t_j) e^{i[(t_j - t)/\tau]}. \]  

The frequency dependence is easily obtained using the \( f = 1/\tau \) relationship.

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**Figure 1.** Time interval of fast solar wind as measured by the Cluster1 satellite on 2004 January 31 (17:30–18:10 UT). Panels (a) and (b) show the velocity, \( V \), and magnetic, \( B \), field components in GSE, respectively, while panel (c) displays \( \theta_{BV} \), the angle between the two previous fields.

in panel (a). Although in this case the data are represented with the same resolution of the velocity field in panel (a), i.e., with a 4 s resolution, in the following part of the paper we will use the highest sampling time of the FGM instrument in nominal mode (22 Hz) to properly describe ion scales. Finally, panel (c) of Figure 1 shows the temporal evolution of the angle between magnetic and velocity fields, \( \theta_{BV} \). The large values of the angle, \( \theta_{BV} > 50^\circ \), indicate that the two vectors are approximately perpendicular, suggesting that there is no connection of the analyzed stream of solar wind with Earth’s foreshock; indeed, the electrostatic waves, typical of a magnetic connection, are not observed on WHISPER during this interval (not shown here).

In order to quantify the turbulence, we compute the power spectrum of the magnetic fluctuations, up to electron scales. Figure 2 shows the total power spectral density (PSD), \( S(f) = \sum_{i=x, y, z} |S_i(f)| \), where \( S_i \) is the PSD of each component of the magnetic field and is defined as

\[ S_i(\tau) = \frac{2\delta t}{N} \sum_{j=0}^{N-1} |W_i(\tau, t_j)|^2, \quad i = x, y, z. \]  

Here \( \delta t \) is the time spacing and \( W_i \) are the Morlet wavelet coefficients for different timescales \( \tau \) and time \( t_j \) (Torrence & Compo 1998),

\[ W_i(\tau, t) = \sum_{j=0}^{N-1} B_j(t_j) e^{i[(t_j - t)/\tau]}. \]  

The frequency dependence is easily obtained using the \( f = 1/\tau \) relationship.

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**Figure 2.** PSD of total magnetic fluctuations measured on Cluster1, by FGM (up to \( \sim 1 \) Hz, solid line), STAFF-SC (up to \( \sim 9 \) Hz, diamonds) and STAFF-SA (\( f > 8 \) Hz, triangles). The red dashed line shows the STAFF-SA noise level on Cluster1. The power-law fit in the MHD range is displayed by the black dashed line, while the spectrum at scales smaller than the ion characteristic scales is described by \( Af^{-\alpha} \exp(-f/f_0) \) (green solid line). Vertical solid bars indicate the proton (in red) and the electron (in blue) characteristic scales (assuming \( f_{p0} = f_0 \)), while the blue filled band denotes the range of scales, \( f \in [0.1, 1] \) Hz, around ion scales.

We use the onboard FGM measurements up to \( \sim 1 \) Hz (solid line) and the Spatio Temporal Analysis of Field Fluctuation experiment/Search Coil (STAFF-SC; Cornilleau-Wehrlin et al. 2003), with a resolution of 25 Hz in the frequency domain \([0.35, 9] \) Hz (diamonds). Finally, we complete the analysis with the SpatioTemporal Analysis of Field Fluctuation experiment/Spectrum Analyser (STAFF-SA) on Cluster1, which provides \( 4 \) s averages of the PSD of the magnetic fluctuations at 27 logarithmically spaced frequencies, between \( 8 \) Hz and \( 4 \) kHz (triangles). The red dashed line shows the instrumental STAFF-SA noise level that becomes significant for \( f > 88 \) Hz, where the signal-to-noise ratio is lower than 3. This region is omitted in Figure 2 to avoid any misunderstanding.

The spectrum in Figure 2 shows the characteristic behavior of the solar wind turbulent cascade (Bruno et al. 2014). At low frequencies, in the MHD range, the distinctive behavior of a power law, \( \propto f^{-1.52} \), is observed (black dashed line). Then, around 0.3 Hz, that is in between the characteristic proton frequencies (i.e., cyclotron frequency, \( f_{cp} \), Doppler-shifted proton Larmor radius, \( f_{pL} = v_p/2\pi\rho_p \), and proton inertia length, \( f_{pL} = v_p/2\pi\lambda_p \) estimated under the assumption of a wavevector parallel to the plasma flow (vertical red bars), a change in the spectral shape is observed. At higher frequencies (\( f > 0.3 \) Hz), the spectrum is steeper and is well described by the exponential model proposed by Alexandrova et al. (2012) for a general description of the whole turbulent spectrum at kinetic scales. The present model

\[ \text{PSD}(f) = Af^{-\alpha} \exp(-f/f_0) \]  

is composed by an exponential with a characteristic frequency \( f_0 \) and with a power-law pre-factor. Therefore, the three free parameters are (i) the amplitude \( A \), (ii) the spectral index \( \alpha \), and (iii) the cutoff frequency \( f_0 \). The exponential model fitting is shown in Figure 2 by the green solid line, including also the
parameters of the fit: \( A \simeq 0.01, \alpha \simeq 2.8, \) and \( f_0 \simeq 46.3 \) Hz. By considering \( f_0 \) related to the Doppler-shifted electron Larmor radius, \( f_\rho = \frac{v_\infty}{2\pi}\rho_\rho \), in agreement with the general spectrum proposed by Alexandrova et al. (2012), \( f_0 \in [0.74 f_\rho, f_\rho] \), we have \( \rho_\rho \in [1.5, 2.1] \) km. This result is in agreement with \( \rho_\rho \) estimated by using directly the electron perpendicular temperature.

In Figure 2, the blue filled band denotes the range of scales, \( f \in [0.1, 1] \) Hz, that are of interest for the investigation of the nature of the turbulent fluctuations around ion scales, which is the aim of the present work. Therefore, in the following part of the paper, we will focus on the high-resolution magnetic field data given by FGM on Cluster1.

Figure 3 shows the PSD of the perpendicular (red solid line) and parallel (blue dashed line) magnetic field fluctuations. The variations of the magnetic field magnitude can be used as a proxy of the parallel (compressive) fluctuations \( \delta B_\parallel = \delta B_\parallel^2 / 2B_0 \), where \( B_0 \) is the mean magnetic field on the whole interval; Perrone et al. 2016), so the corresponding energy is

\[
\mathcal{W}_\parallel^2(\tau, t) = \mathcal{W}_{B|\parallel}^2(\tau, t),
\]

while the energy of the perpendicular (Alfvénic) fluctuations is defined as

\[
\mathcal{W}_\perp^2(\tau, t) = \mathcal{W}_{B|\perp}^2(\tau, t) - \mathcal{W}_\parallel^2(\tau, t),
\]

where \( \mathcal{W}_\parallel^2(\tau, t) \) is the total energy of the magnetic fluctuations. The bias in the spectrum due to the quantization noise, not shown in the figure, is \( q^2 / 12f_\rho \sim 4 \cdot 10^{-7} \) nT² Hz⁻¹ (Widrow & Kollár 2008), where \( q \) is the digitization of the instrument (\( 10^{-2} \) nT for FGM in the solar wind mode) and \( f_\rho \) is the sampling frequency (22 Hz), and by assuming that the noise is uniformly distributed over the entire spectral range. However, although the quantization noise is very low, the comparison between FGM and STAFF data shows that the two spectra start to deviate for \( f > 1 - 2 \) Hz, meaning that the instrumental noise could become important at frequencies higher than 1–2 Hz.

Figure 3 shows that, although in the inertial range the energy stored in the perpendicular direction is much stronger than the compressive one, around ion scales the compressive energy increases, meaning that the contribution of the parallel magnetic fluctuations becomes important at kinetic scales (Alexandrova et al. 2007, 2008; Salem et al. 2012; Kiyani et al. 2013; Perrone et al. 2016) and, in particular, in the frequency range around the spectral transition (\( f \in [0.1, 1] \) Hz; blue filled band). The small bump in the compressive energy around 0.25 Hz corresponds to the satellite spin (\( \tau = 4 \) s).

3. Intermittency, Non-Gaussianity, and Phase Coherence

The spectra, in general, provide information about the global properties of the turbulent activity, but only a local analysis of the fluctuations enables us to understand the details of turbulence. In this context, panels (a) and (b) of Figure 4 show the evolution of the Local Intermittency Measure (LIM) for the parallel and perpendicular magnetic energy, respectively. The LIM is defined as the energy of magnetic fluctuations, as a function of time and scales, normalized at each time point by a mean spectrum over the whole time interval:

\[
I_{\perp,\parallel}(\tau, t) = \frac{\langle |\mathcal{W}_{\perp,\parallel}(\tau, t)|^2 \rangle}{\langle |\mathcal{W}_{\perp,\parallel}(\tau, t)|^2 \rangle}. \tag{6}
\]

The curved black lines, on each side of the plots in Figure 4, represent the cone of influence where the Morlet coefficients are affected by edge effects (Torrence & Compo 1998). Nonuniform distribution of energy is observed in both parallel and perpendicular components with the appearance of localized energetic events covering a certain range of scales, which are easily recognized by the red color. This is an indication of the presence of coherent structures in the system, which will be described in detail in Section 4. These intermittent events are strictly connected with the strong variations of the magnetic field components (see, e.g., the variation between 17:40 and 17:50 in panel (b) of Figure 1), which is highlighted by the variation of the inverse of the proton cyclotron frequency (horizontal black lines in Figure 4).
Let’s consider the phase coupling between the magnetic components during the analyzed time interval. Figure 5 shows the phase coherence, \( R_\Phi(\tau, t) \), between two components, \( B_i \) and \( B_j \), defined as (Grinsted et al. 2004; Lion et al. 2016)

\[
R_\Phi^2(\tau, t) = \frac{|S(\tau)\tilde{W}(t, \tau)\tilde{W}^*(t, \tau)|^2}{S(\tau)|\tilde{W}(\tau, t)|^2 \cdot S(\tau)|\tilde{W}^*(\tau, t)|^2},
\]

where \( S \) is a compound smoothing operator for frequencies and time, \( S(\tilde{W}(\tau, t)) = S_1(S_2(\tilde{W}(\tau, t))) \), with

\[
S_1(\tilde{W}(\tau, t)) = \tilde{W}(\tau, t)C_1^{-1/2},
\]

\[
S_2(\tilde{W}(\tau, t)) = \tilde{W}(\tau, t)C_2\Pi(0.6/\tau),
\]

with \( C_1 \) and \( C_2 \) being the normalization constants (Grinsted et al. 2004), \( \Pi \) the rectangular function, and 0.6 the scale decorrelation length for the Morlet wavelet (Torrence & Compo 1998). By definition, the values of \( R_\Phi(\tau, t) \) are between 0 (no coherence, in white) and 1 (full coherence, in black).

We consider the phase coherence between magnetic components in a reference frame where \( z \) is aligned with a magnetic field \( B_0 \) averaged on the whole time interval \((e_z = e_b)\), \( x \) is perpendicular to \( B_0 \) in the plane spanned by it and the radial direction \((e_x = e_b \times e_z)\), and \( y \) closes the right-hand reference frame \((e_y = e_b \times e_x)\). In this case, we are considering the global frame defined on 40 minutes. In Sections 4 and 5 a local frame will be assumed by considering a magnetic field at scales on the same order of scales of the individual turbulent structures. It is worth pointing out that the choice of a particular mean magnetic field could lead to significant differences in physical results (Chen et al. 2011; Matthaeus et al. 2012; TenBarge et al. 2012). However, in our case, both the magnetic frames produce almost the same results since the angle between the global and the local magnetic field is small (its histogram, not shown here, is peaked around 10°).

Figure 5 shows the phase coherence of each couple of magnetic field components, where localized regions in time of high coherence are found, which cover a certain range of scales, including the frequency range \( f \in [0.1, 1] \) Hz (\( \tau \in [1, 10] \) s), as in the case of intermittency for both perpendicular and parallel magnetic energy (Figure 4).

Keeping the same reference frame, we investigate the Gaussianity of the magnetic fluctuations as a function of scale (or frequency) by using the fourth-order moment of each component. We define the flatness (or kurtosis) of \( B_i \) as

\[
\mathcal{F}(\tau) = \frac{\langle \tilde{W}(\tau, t)^4 \rangle}{\langle \tilde{W}(\tau, t)^2 \rangle^2},
\]

where \( \tilde{W} \) is the real part of the wavelet coefficient and \( \tau = 1/f \). If \( \mathcal{F}(\tau) = 3 \), the probability distribution function (PDF) of the corresponding component of magnetic field fluctuations is a standard normal distribution, whereas if \( \mathcal{F}(\tau) > 3 \), the PDF is not a Gaussian distribution, showing fat tails.

Figure 6 shows \( \mathcal{F}(f) \) for \( B_z \) (black solid line), \( B_y \) (red dashed line), and \( B_x \) (blue dotted-dashed line). The value of the flatness for a standard normal distribution (horizontal green dotted line) is given as a reference. We observe that the flatness of both parallel and perpendicular magnetic field fluctuations departs from the normal distribution value, reflecting a nonhomogeneous distribution of the turbulent fluctuations as already observed in the maps of the LIM (Figure 4). Moreover, after an initial increase of \( \mathcal{F}_z \), the flatness of both perpendicular (\( \mathcal{F}_x \) and \( \mathcal{F}_y \)) and parallel (\( \mathcal{F}_z \)) fluctuations becomes nearly constant around ion scales (blue filled band). However, for \( f \sim 1 \) Hz, i.e., where the FGM data start to deviate from STAFF data, \( \mathcal{F}_z \) begins to decrease. This behavior could be due to the fact that the noise becomes important for \( f > 1 \)–2 Hz. Indeed, the noise is expected to have Gaussian statistics; thus, \( \mathcal{F}_z \) might approach the constant value expected for a Gaussian distribution. However, a decrease in flatness, related to the frequency location of the break, has been already observed in the literature by Wu et al. (2013) and Telloni et al. (2015). In particular, Wu et al. (2013) observed a flatness decrease in all the magnetic components, arguing that it is of physical origin, due to an additional ingredient of incoherent dynamics.

Therefore, in addition to the intermittency and phase coherence, the ion scales appear also characterized by the departure from Gaussianity of the PDFs. However, the expected behavior for the intermittency to increase with a
decreasing scale is not observed in this particular range of scales, where the flatness is almost constant. Moreover, it is worth pointing out that $F_{\gamma}$ reaches a higher value of saturation with respect to $F_{X}$ and $F_{Y}$. (even though most of the energy is stored in the $B_{z}$ component), meaning that the parallel direction could represent a preferential channel for the evolution of nonlinear effects at kinetic scales.

To focus on the range of scales around ion scales and to compare the present analysis with the results in slow solar wind described in Perrone et al. (2016), we use a bandpass filter based on the wavelet transform (Torrence & Compo 1998; He et al. 2012; Roberts et al. 2013; Perrone et al. 2016), for the range $f \in [0.1, 2]$ Hz, defined as

$$
\delta b_i(t) = \frac{\delta j \delta t^{1/2}}{C_{j} \psi_{0}(0)} \sum_{j=j_{l}}^{j_{u}} \tilde{W}_{j}(a_{j}, f_{f}, t) \frac{a_{j}^{1/2}}{a_{j}}, \tag{11}
$$

where $j$ is the scale index and $\delta j$ is the constant step in scales; the factor $\psi_{0}(0) = \pi^{1/4}$, and the value of the constant $C_{j}$, derived from the reconstruction of a $\delta$ function using the Morlet wavelet, is 0.776 (Torrence & Compo 1998). Finally, $\tau(f) = 0.5$ s and $\tau(f_{f}) = 10$ s.

Figure 7 displays the PDFs of $\delta b_x$, $\delta b_y$, and $\delta b_z$, normalized to their own standard deviations, $s(\delta b_i)$, whose values are indicated in the corresponding panels. Most of the energy is stored in the perpendicular directions, as already observed in the spectra for both perpendicular and parallel magnetic fluctuations (Figure 3). The PDFs are compared to their corresponding Gaussian fits (black dashed lines), showing the presence of fat non-Gaussian tails in each component of magnetic field fluctuations with respect to the background magnetic field, especially in the $z$ direction as expected from the higher values of $F_{\gamma}$ with respect to $F_{X}$ and $F_{Y}$. The vertical black solid lines in each panel indicate the position of three standard deviations of the Gaussian fit for the corresponding magnetic fluctuations, which include 99.7% of the Gaussian contribution. All the events that exceed these limits, $|\delta b_i| > 3s(\delta b_i)$, contribute to the non-Gaussian part of the PDFs.

To investigate the relation between the non-Gaussianity of the magnetic fluctuations and the phase coherence between the components, in Figure 8 we consider about 40 s out of 40 minutes of the whole interval of fast solar wind. Panel (a) shows the time evolution of turbulent magnetic fluctuations $\delta b_i$ (black line), $\delta b_y$ (red line), and $\delta b_z$ (blue line), as defined in Equation (11). In panel (b) we display the total turbulent magnetic energy, $\delta b_{\text{tot}}^{2} = \delta b_{x}^{2} + \delta b_{y}^{2} + \delta b_{z}^{2}$, where the red horizontal dashed line indicates the threshold, which will be considered in the following part of the paper to select intermittent events. The threshold is defined as $3\sigma$ of the distribution law for the amplitudes of a Gaussian vectorial field compared to $\delta b_{\text{tot}}^{2}$. Finally, in panel (c) we show $R_{ij}(f_{0}, t) > 0.6$ for the highest frequency considered in the selection of intermittent events ($f_{0} = 2$ Hz). One can see that we observe very strong peaks of coherence, i.e., magnetic field components are strongly coupled. These peaks are localized in time, and very often (e.g., between 20 and 30 s) they correspond to strong peaks in magnetic energy (see panel (b)). However, sometimes strong coherence between two events could represent a preferential channel for the evolution of nonlinear effects at kinetic scales.

Figure 7. PDFs of (a) $\delta b_x$, (b) $\delta b_y$, and (c) $\delta b_z$, normalized to their own standard deviations, $s(\delta b_i)$, and compared to their corresponding Gaussian fits (black dashed lines). Vertical black solid lines show the position of three standard deviations of each Gaussian fit. The values of $s(\delta b_i)$, the limits for the Gaussian contribution, $3s(\delta b_i)$, and the flatness, $F_{\gamma}$, are also indicated in each panel.

Figure 8. (a) Temporal evolution of turbulent magnetic fluctuations, $\delta b_i$ (see Equation (11)), in a considered zoom of about 40 s. (b) Total magnetic energy, $\delta b_{\text{tot}}^{2}$, where the red horizontal dashed line indicates the threshold in the selection of intermittent events. (c) Phase coherence $R_{ij}(f_{0}, t) > 0.6$, with $f_{0} = 2$ Hz being the highest frequency considered for the magnetic fluctuations.
components, e.g., \(\sim 10 \text{ s}\), corresponds to small amplitude in \(\delta b_{gt}\), which is not selected by our threshold, is probably overestimated to select all the coherent structures.

This result verifies the link between intermittency, non-Gaussian fluctuations, and phase coherence between magnetic field components, in agreement with the studies of Koga et al. (2007) and Lion et al. (2016). Moreover, thanks to this link, we can assert that the selection of intermittent events in a turbulent signal is almost independent of the choice of a particular magnetic field component, as far as all components are coupled.

In the present paper, we select intermittent events by considering a threshold \((\sim 1.2 \text{ nT}^2)\) on the total turbulent magnetic energy, \(\delta b_{tot}\), in the range scale \(f \in [0.1, 2] \text{ Hz}\), as discussed above. It is worth pointing out that the same results, which will be described in the following part of the paper, can be found if we select intermittent events by considering compressive fluctuations, \(\delta b_{c} = \delta [b]\), as in Perrone et al. (2016). For the whole time interval (40 minutes) of fast solar wind, we get about 140 peaks, meaning that coherent structures cover \(\sim 30\%\) of the analyzed stream (where the coherent time is evaluated as 2.5 times the timescale of each structure, without overlapping).\(^{2}\) In fast solar wind the coherent structures appear to be somewhat less frequent with respect to the interval of slow solar wind described in Perrone et al. (2016), in which \(\sim 40\%\) of the interval was covered by coherent events. A detailed analysis of the structures in fast solar wind will be presented in the following sections of the paper.

### 4. Coherent Structures

To study the nature of the intermittent events, we perform a minimum variance analysis around each selected peak, identifying magnetic fluctuations that are well localized in space and with regular profiles. These characteristics are inherent properties of coherent structures. However, since the automatic method for the selection of intermittent events recovers the most energetic peaks, it is possible that if there are few of them very close they refer to the same event. In order to avoid an overestimation of the detected events, we check all the selected peaks and confidently identify 101 events. In particular, we find 19 isolated vortices, 32 vortex chains, and 18 current sheets. For the latter, only 6 current sheets are isolated, while the other 12 are recovered at the center of vortices or sometimes at their boundaries. Moreover, for the remaining 32 structures the nature is not clear. However, no strongly compressive structures, such as solitons, magnetic holes, or shocks, have been detected, in stark contrast to what is observed in slow solar wind.

In the following, we present three examples of observed coherent structures of different nature. In Figure 9 (as well as Figures 11 and 13), panel (a) displays the modulus of the raw magnetic field measurements, namely, large-scale magnetic field, as observed by the four satellites (different line styles), where the FGM noise at \(f > 2.5 \text{ Hz}\) is taken off. The red double arrow indicates \(\Delta \tau\), i.e., the characteristic temporal scale of the structures (see Perrone et al. 2016, for details), while the two vertical dashed lines denote the total width of the structures \((\Delta \tau')\).

Panel (b) shows magnetic fluctuations \(\delta b_{i}\) (with \(i = x, y, z\), defined by Equation (11), in a BV reference frame that takes into account the directions of the local mean magnetic field \(b_{0}\) and flow velocity \(v_{0}\) evaluated within each structure timescale \(\Delta \tau'\); \(z\) is aligned with \(b_{0}\), \(e_{z} = e_{b}\) (blue lines), \(x\) is aligned with \(v_{0}\) in the plane perpendicular to \(b_{0}\), \(e_{x} = (e_{b} \times e_{y}) \times e_{b}\) (black lines), and \(y\) closes the right-hand reference frame, \(\delta b_{x}\) and \(\delta b_{y}\) are aligned with \(e_{x}\) and \(e_{y}\), respectively, and \(e_{z} = (e_{x} \times e_{y})\). Panel (c) displays the modulus of magnetic fluctuations \(|J|\) (red solid line), and current densities \(J_{b}\) (green solid line) and \(J_{c}\) (blue solid line), as observed by the four satellites, where the FGM noise at \(f > 2.5 \text{ Hz}\) is taken off. Panels (d) and (e) show, respectively, the electron density and its modulus. The time of each satellite is shifted taking into account the time delays with respect to Cluster 1. The horizontal black solid line is given as a reference for \(b_{0} = 0 \text{ nT}\). (c) Modulus (black dashed line) and components (in the BV frame) of the current density. (d) Electron density obtained by the spacecraft potential. The vertical black dashed lines indicate \(\Delta \tau'\), corresponding to the total extension of the structure (\(\Delta \tau' \sim 13.5 \beta_{c}\)). (e and f) Configuration of Cluster satellites in the BV frame: black diamonds for Cluster1, red triangles for Cluster2, blue squares for Cluster3, and green circles for Cluster4. The arrows indicate the direction of the normal (black), local flow (red), and local magnetic field (blue), while the black dashed lines represent the plane of the structure.

\(^{2}\) Looking at each structure recovered by the selection method, we observe that coherent fluctuations are somewhat larger than the timescale, defined as the time range between two minima containing a maximum of energy over the threshold. The same definition of coherent time has been used in Perrone et al. (2016).
\[ e_x = e_y \times e_z \] (red lines). The time of each satellite is shifted, taking into account the time delays with respect to Cluster1. Moreover, panel (c) displays the evolution of the current density \( J \), calculated by using the curlometer technique (Dunlop et al. 1988, 2002), based on four-point measurements of Cluster. The three components of \( J \) are given in the BV frame, while the modulus, \( |J| \), is shown by the dashed line.

To have information on the plasma quantities, panel (d) shows the behavior of the electron density, \( n_e \), evaluated by using the satellite potential (Pedersen 1995; Pedersen et al. 2001), from the Electric Field and Wave (EFW) experiment (Gustafsson et al. 1997). These measurements have five vectors per second time resolution, which is much better than particle measurements on Cluster, which have 4 s time resolution. However, the spacecraft potential is subject to a strong spin effect, as well as charging effects due to different parts of the spacecraft being illuminated as it spins. In order to have sub-spin time resolution, the spin effect needs to be removed. This can be done, provided that the density is stable, by constructing a series of phase angles for the spacecraft and binning the corresponding potentials by angle as opposed to time. By using the median value of each bin to reduce the effects of extreme values and subtracting the mean in the interval studied, the charging fluctuation can be obtained as a function of phase angle. This can be fitted with a model and subtracted from the potential measurement at each spacecraft phase angle. More details are provided in Roberts et al. (2017).

Finally, panels (e) and (f) give the configuration of the four Cluster satellites in the BV frame, by using different symbols and colors: black diamonds for Cluster1, red triangles for Cluster2, blue squares for Cluster3, and green circles for Cluster4. The arrows display the directions of the normal of the structures, \( n \) (black), determined by using the timing method (see Section 5), of \( v_0 \) (red), and of \( b_0 \) (blue). Moreover, the black dashed lines indicate the plane of the structures.

### 4.1. Current Sheet

The first example of coherent structure is shown in Figure 9. It is an incompressible structure with a component, \( \partial b_x \), that changes sign and is perpendicular to the local magnetic field. The other two components have fluctuations of very small amplitude. The reversal of the component of maximum variation is in the middle of the structure, where the large-scale magnetic field has its local minimum (panel (a)) and a peak in the current is recovered (panel (c)). Minimum variance analysis applied to this structure confirms the result that it is a one-dimensional (i.e., linearly polarized) Alfvénic structure: the direction of the maximal variation \( e_{max} \) is perpendicular to the direction of \( b_0 \) (e_{max} \simeq 86^\circ), while the current density is almost parallel. The four satellites observe the same amplitudes for the fluctuations, which is consistent with a planar geometry. Moreover, in the center of the structure, a peak in the density is found (panel (d)), meaning that the plasma is confined inside the structure. This event can be identified as a current sheet. Finally, panels (e) and (f) show that the normal to the structure, \( n \), is almost perpendicular to \( b_0 \), while it is almost parallel to \( v_0 \). The thickness of the current sheet, estimated by using the timing method (see Perrone et al. 2016, for details), is \( \Delta r \simeq 2.5 \rho_p \) (with \( \Delta r \simeq 13.5 \rho_p \) being the total extension of the structure), and its velocity in the plasma frame is \( V_0 \simeq -23 \pm 209 \text{ km s}^{-1} \). Therefore, it is almost convected by the flow, as expected for a current sheet.

A well-known one-dimensional current sheet equilibrium is the Harris current sheet (Harris 1961), which is a stationary solution of the Maxwell–Vlasov system. This simple model could represent analytically thin current layers at kinetic scales (Greco et al. 2016). The magnetic field profile is given by a 1D hyperbolic-tangent profile \( B = B_0 \tanh(x/L) \), where \( x \) is the spatial coordinate and \( L \) is the half-width of the current sheet. The corresponding profile for the current density is \( J \propto (B_0/L)\cosh^2(x/L) \). Figure 10 shows the three components of the magnetic field fluctuations (panel (a)) and of the current density (panel (b)) in the BV frame for the discontinuity in Figure 9, as a function of the spatial coordinate, defined as \( x = V \times t \), where \( V \) is the velocity of the current sheet in the satellite frame and \( t \) is the time as indicated in Figure 9. The dashed lines denote the Harris profile for both magnetic field and current, while the red double arrow indicates \( \Delta r \) in km.

### 4.2. Vortex

Another example of coherent structure observed in this stream of fast solar wind is shown in Figure 11. The background magnetic field (panel (a)) is characterized by a...
modulated fluctuation, observed by the four spacecraft, with a local maximum in the middle of the structure. The corresponding fluctuations, $\delta b_y$, are more localized, with the principal variation in the plane perpendicular to the local magnetic field, $b_y$, and small compressive fluctuations, $\delta b_z \ll \delta b_y$. Moreover, a minimum variance analysis indicates that the intermediate component is not negligible, i.e., the event is a bi-dimensional structure, and both the directions of maximum and intermediate variance are in the plane perpendicular to $b_0$ ($\theta_{\text{max}} \approx 88^\circ$ and $\theta_{\text{int}} \approx 87^\circ$), while the direction of minimum variance is along $b_0$ ($\theta_{\text{min}} \approx 3^\circ$). Panel (c) displays the current density, $J$, which is mainly in the direction parallel to $b_0$, while panel (d) shows the electron density, which exhibits a fluctuating behavior ($\delta n_e \sim 0.1 \text{ cm}^{-3}$) and is anticorrelated with the background magnetic field, with a local minimum in the center of the structure. Finally, panels (e) and (f) show the result of the timing method for the normal of this structure, which is almost perpendicular to $b_0$ ($\theta_{\alpha B} \approx 84^\circ$) but almost parallel to $v_0$. The velocity of propagation along the normal and in the plasma frame is $V_0 \approx -27 \pm 240 \text{ km s}^{-1}$. The characteristic scale for this two-dimensional structure is $\sim 5.5 \rho_p$, while the total width, corresponding to $\Delta x'$, is $\sim 27 \rho_p$.

The structure looks like a monopolar Alfvén vortex (Pevtsov & Pokhodiev 1992; Alexandrova 2008), crossed by the four satellites more or less at the same distance from the center. In general, a monopolar vortex is a tubular structure that is aligned with the magnetic field direction and is a nonlinear analytical solution of the ideal, incompressible MHD equations. However, in this case, the structure shows a pressure balance, i.e., an anticorrelation between density and magnetic field, not predicted by the incompressible model. To verify the vortex topology of this structure, we fit the observed fluctuations with the analytical model for a monopolar Alfvén vortex, derived from the vector potential, $A$ (Pevtsov & Pokhodiev 1992; Alexandrova 2008; Roberts et al. 2016). The longitudinal current is given by $J = \nabla \times A$.

The vortex is modeled in the $x' - \eta$ plane, which are two directions perpendicular to the vortex axis, and the $x'$-axis makes an angle of $10^\circ$ with the relative path of the spacecraft through the plasma. Moreover, the angle of the vortex axis with respect to the magnetic field direction is $2^\circ$. The vortex is modeled with a constant amplitude of $A_0 = -0.3$, and the vortex diameter is set at $30 \rho_p$. This is motivated by the value obtained from timing analysis and is much larger than the interspacecraft distances, consistent with all spacecraft seeing similar fluctuations. Finally, the impact parameter, i.e., the distance from the center at $x' = 0$, is $-0.05 a$, where $a$ is the radius of the vortex.

Panels (a) and (b) of Figure 12 show the perpendicular fluctuations of the vortex solution $\delta b_y(x', \eta)$ and $\delta b_y(x', \eta)$, respectively, normalized to the local mean magnetic field, $b_0$, while panel (c) shows the normalized longitudinal current, $\delta J_x(x', \eta)$. The spatial dimensions are given in units of the proton Larmor radius, $\rho_p$. The relative path of the virtual spacecraft is denoted by the arrows. The analytical solution of the Alfvén vortex and Cluster data are compared in panels (d)–(f) of Figure 12 and show good agreement for both magnetic components and current density.

We observe 19 structures similar to the example in Figure 11. Moreover, only two of them present a compressive nature, where the ratio between the parallel and perpendicular magnetic field fluctuations is higher than 0.35 (Perrone et al. 2016).

In order to determine the possible nature of these structures, we perform an analysis on the polarization (He et al. 2011, 2012; Telloni et al. 2015), though here we are studying structures and not waves (we do not have a specific frequency for them, but a range of scales is covered). For all the vortices (except for one) we find, in the satellite frame and in the ($\delta b_y - \delta b_x$) plane perpendicular to the normal, an elliptical polarization with the major axis perpendicular to the local mean magnetic field and right-handedness with respect to the direction of the normal (which in the wave approximation represents the $k$ direction). This result is consistent with previous studies of the dissipation range (e.g., Goldstein et al. 1994) and with the fact that in the case of an Alfvén wave the increase of the angle between $k$ and $B_0$ produces a change in the polarization from left- to right-handed polarization (Gary 1986).

However, by considering the polarization in the plasma frame (i.e., by considering the sign of $\gamma_0$), the result changes. If the velocity of the structure is smaller than the velocity of the
solar wind along the normal, the propagation is antiparallel to the normal, so the observed polarization is inverted in the plasma frame (i.e., left-handed polarization). Since the observed vortices have both positive and negative $V_0$, the polarization can be both right- and left-handed in the plasma frame. Anyhow, sometimes the value of $V_0$ can be very small and/or its error may be important. Therefore, a definitive conclusion is very difficult.

Finally, we compare the ratio between the parallel and the total magnetic energy with what is expected for kinetic Alfvén waves (Boldyrev et al. 2013). In the case of the vortices the ratio is very low, i.e., about one order of magnitude lower than expected for kinetic Alfvén waves.

### 4.3. Vortex Chain?

The last example of observed structure is given in Figure 13. The large-scale magnetic field is characterized by different oscillations, and the same behavior is observed in the components of the magnetic field fluctuations in panel (b), showing significant oscillations in the plane perpendicular to $b_0$ ($\theta_{\text{max}} \simeq 88^\circ$ and $\theta_{\text{min}} \simeq 7^\circ$) as the current density. Moreover, the principal spatial gradient is $\nabla_i \gg \nabla_0$, which gives $n \perp b_0$ (see panels (e) and (f)). Furthermore, the normal of the structure is almost parallel to $v_0$, and the velocity of propagation in the plasma rest frame is $V_0 \simeq -(52 \pm 580)$ km s$^{-1}$. The characteristic scale for this structure, indicated by the red double arrow, is $\sim 6.1\rho_p$, while the total width is $\sim 89\rho_p$. Finally, as in the case of the vortex in Figure 11, the electron density $n_e$ (black line) and $\delta n_e$ (red line) are anticorrelated to the large-scale magnetic field, meaning that this event is also in pressure balance.

Figure 14 shows five incomplete electron pitch angle distributions, taken during about 20 s surrounding the center of the structure. In particular, these plots are cuts of the distribution at pitch angles $0^\circ$ (blue line), $90^\circ$ (black line), and $180^\circ$ (red line). Some gaps in the lines are due to missing data. Moreover, the electron pitch angle distributions are not corrected from the spacecraft potential also because of missing data. However, the spacecraft potential is less than 9 eV since this is the lowest energy PEACE measures and no photoelectrons are visible.

In its most common operating mode, the PEACE electron spectrometer (Johnstone et al. 1997; Fazakerley et al. 2009) returns a 2D pitch angle distribution from one or both of its two sensors every spacecraft spin (i.e., $\sim 4$ s). Each pitch angle distribution is constructed from two energy sweeps taken 2 s apart, when a sensor’s field of view is looking along and against the magnetic field direction, respectively. An individual sweep is typically completed in $\sim 0.125$ s. Thus, it is possible to examine the electron properties of small-scale structures using PEACE, albeit without complete pitch angle coverage, by considering an individual sweep that was taken during the passage of that structure over the spacecraft.

In Figure 14 the time of the cuts corresponds to the vertical green dotted-dashed lines in Figure 13 for pitch angles $90^\circ$ and $180^\circ$, while pitch angle $0^\circ$ is taken 2 s later. We observed a typical strahl signature for pitch angle $0^\circ$ in each panel of Figure 14, meaning that it does not change over the entire 20 minutes considered. No information is available in panel (ii) owing to the loss of coverage.

Let’s consider now the electron distributions for pitch angles $90^\circ$ and $180^\circ$. Panels (iii) and (iv) of Figure 14 are from two sweeps taken at the center of the structure ($t = 0$) and 4 s later ($t = +4$ s), respectively. At these times, which correspond to the vortex central region, the electron distributions seem to be typical solar wind distributions: almost isotropic with a spectral break between the core and the halo at about 60 eV. No evidence of accelerated particles or beams is observed. Moreover, in panel (iv) there is no data from pitch angle $90^\circ$.
and several vectors, i.e., the normal of $\theta_B$. The panels are the same as in Figure 9. Moreover, the vertical green dotted-dashed lines in each panel denote the time of the electron pitch angle distributions in Figure 14.

Figure 13. Example of an interaction of Alfvén vortices, centered at 17:37:33.6 UT and with $\Delta r \simeq 89\rho_e$. The panels are the same as in Figure 9. Moreover, the vertical green dotted-dashed lines in each panel denote the time of the electron pitch angle distributions in Figure 14.

because at that time the magnetic field direction changes significantly, losing coverage.

A different situation is found close to the vortex boundary ($t = -4$ s and $t = +8$ s), where the theoretical current model for a vortex presents a discontinuity. Here, in panels (ii) and (v), the electron distributions are atypical, with an increase in the phase space density, localized in energy at $\sim 100$ eV, in both antiparallel and perpendicular electrons. These distributions could be unstable and generate waves, such as Langmuir waves. Finally, panel (i) shows the electron distribution at $t = -8$ s, which is close to a current sheet or another vortex boundary and is slightly atypical, with an increase in the phase space density around $\sim 100$ eV for pitch angle $180^\circ$.

The structure in Figure 13 could be interpreted as a chain of three adjacent vortices, crossed by the spacecraft at different distances from the center of each vortex. It is interesting that, within the vortices, the electron distribution functions are typical solar wind distributions, but close to their boundaries electrons beams are observed at pitch angles $90^\circ$ and $180^\circ$, while in pitch angle $0^\circ$ we do not see any changes. However, any signature of a similar amplitude to those observed in pitch angles $90^\circ$ and $180^\circ$ would be small compared to the signature of the strahl. Unfortunately, due to the low time resolution of the measurements, we are not able to follow the evolution of the electron pitch angle distribution in each point of the structure. Even worse is the case of ion measurements, whose time resolution on the considered solar wind stream is so low ($\sim$1 minute in the low geometric factor side of the HIA instrument for solar wind measurements) that no detailed information is available, and also the angular resolution is still quite low to study the deformation of the velocity distribution (B. Lavraud 2017, private communication).

On the other hand, the structure could also be described as an interaction between vortices. By assuming, for example, that the two initial vortices are centered around $-5$ and $5$ s with an isolated extension of about $8$ s each, we could expect that the center of the total structure corresponds to the region of interaction. From panel (c), the signs of the vortex currents suggest that the Lorentz force could attract the two vortices. Moreover, looking at the shape of the magnetic fluctuations in panel (b), it seems that the vortex on the left side is more distorted with respect to the right one. This could be due to different and opposite velocities of the vortices (higher for the vortex on the right side) or to the different initial amplitudes of the vortices, which produce a different level of distortion at this stage of the interaction. This stage, in fact, could be only a transition phase for this interaction between vortices, and this configuration could collapse later in a single larger vortex (Novikov & Sedov 1979).

5. Multisatellite Analysis

The Cluster mission provides a unique opportunity to determine the three-dimensional, time-dependent characteristics of small-scale structures, using four-point measurements given by identical instrumentation on the four satellites. Indeed, multisatellite observations exhibit a connection between space and time: the same physical observables are measured not only at different points in space but also at different instants in time. To exploit this opportunity, we use the timing method (Schwartz 1998; Perrone et al. 2016) to characterize the coherent structures observed in this interval of fast solar wind.

The timing method is based on time and space separations and allows us to determine the velocity, $\mathbf{V}$, and the direction of propagation, $\mathbf{n}$, of a locally planar structure moving with a constant speed in the spacecraft frame. All the details about the method and the conditions of its validity can be found in Section 4.2 of Perrone et al. (2016). In the present work, the timing technique allows us to study only a subset of 33 structures (out of 101), for which the method maintains validity and we are sure to properly determine $\mathbf{n}$ and $\mathbf{V}$.

Figure 15 shows the distributions of the angles between the local magnetic field $\theta_B$ and several vectors, i.e., the normal of the structure, the directions of maximal and minimum variance, and the distribution of the angle between $\mathbf{n}$ and the local solar wind velocity in the perpendicular plane, to statistically characterize the geometry and the properties of the observed coherent structures. In particular, $\theta_B$ (black solid line) is always close to $\sim 90^\circ$, meaning that all the observed coherent structures have a perpendicular wavevector anisotropy.
and the direction of maximal variance $\theta_{\text{max}}$ (blue dotted-dashed line), and (iii) minimum variance $\theta_{\text{min}}$ (red dashed line), and of the angle between $n$ and the local solar wind velocity in the $(x, y)$-plane of the $BV$ reference frame ($\theta_{BV}$; green solid line).

\[ (k_\parallel \gg k_\perp), \] where $\theta_{BV}$ (green solid line) is peaked around $\sim 20^\circ$, where $V_\perp$ is the local solar wind velocity in the $(x, y)$-plane of the $BV$ reference frame. These results are in agreement with the case of slow solar wind studied by Perrone et al. (2016). On the other hand, $\theta_{\text{min}}$ (red dashed line), the angle between $b_\parallel$ and the direction of minimal variance, shows a uniform distribution in the range between $0^\circ$ and $80^\circ$. Moreover, $\theta_{\text{max}}$ (black solid line), the angle between $b_\parallel$ and the direction of maximal variance, is almost peaked around $\sim 90^\circ$, emphasizing the absence of compressive structures in fast solar wind. Here, the structures are mostly Alfvénic ($b_\parallel \gg b_\perp$), with very small compressive components with respect to slow solar wind structures. These results, in comparison with the analysis done by Perrone et al. (2016), suggest a different nature, in terms of features of coherent structures, between fast and slow streams of solar wind.

To study more in detail the differences between the two streams, in Figure 16 we statistically investigate the velocity of the structures along the normal direction in the plasma frame, $V_0 = V - V_w \cdot n$, where $V_w$ is the local mean speed of the solar wind and $dV_0$ is the corresponding error. For the details, please refer to Section 4.2.2 of Perrone et al. (2016). It is worth pointing out that $dV_0$ is larger in the case of fast solar wind than in the slow wind case because it is proportional to the value of the wind speed (the error on the solar wind velocity is estimated as 5% of the value of the speed). Figure 16(a) shows $V_0$ for the 33 structures, ordered by increasing value, with the corresponding error bars. Contrary to what is found for the case of slow solar wind, in which 25% of the observed structures had significant velocities different from zero (Perrone et al. 2016), in the present stream of fast solar wind all the structures are simply convected by the flow. Only a clear example of no convected structure is observed, but it is probably due to the incertitude in the identification of the range of localization. Moreover, the distribution of $V_0$, normalized to the Alfvén speed $V_a$ (black solid line) and to the proton thermal speed $V_{th}$ (blue dotted–dashed line) in panel (b) of Figure 16, also suggests the same result, where the characteristic velocities are calculated in the upstream region for each structure, known from the sign of $V_0$. Both distributions are peaked around 0 and vary between $[-1, 2]V_a$ and $V_{th}$. No fast structures are found, contrary to the case of slow solar wind (Perrone et al. 2016). Only an event of very fast structure ($V_0 \sim 6V_a$) is observed, corresponding to the no-convected structure in panel (a), which in any case does not have a statistical meaning.

### 6. Conclusions and Discussion

In this paper, we have investigated the nature of magnetic turbulent fluctuations around ion scales in a stream of fast solar wind, by using high-resolution $Cluster$ data. The results are complementary to the recent statistical study in slow wind plasma by Perrone et al. (2016).

The study of the distribution of energy in time and frequencies shows the presence of localized regions in time that cover a certain range of scale. The same nonhomogeneous distribution of energy localized in time, covering certain frequencies, was already highlighted in slow solar wind (Perrone et al. 2016). Thus, independently of the streams, the solar wind ion scales appear to be characterized by a strong intermittency that could play an important role in dissipation and particle energization.

A detailed study of magnetic fluctuation in the range $f \in [0.1, 2]$ Hz has shown that this region is also characterized by a high phase coherence between the magnetic components and by a significant non-Gaussianity. The departure from Gaussianity of the turbulent fluctuations reflects a nonhomogeneous (intermittent) distribution of the turbulent energy, with the appearance of structures characterized by a finite degree of phase synchronization. Therefore, intermittency, phase coherence, and non-Gaussian fluctuations are found to be strictly
related, in agreement with previous studies (Koga et al. 2007; Lion et al. 2016).

We show that, at ion scales, the observed intermittency is related to convected coherent structures with a strong wavevector anisotropy in the perpendicular direction with respect to the local magnetic field ($k_{b} \gg k_{l}$). In particular, the fast solar wind appears to be dominated by Alfvén vortices (isolated or in chains), with a small compressive part (for most of them the ratio between the parallel and the total magnetic energy is less than 10%), and by several current sheets aligned with the local magnetic field, convected by the flow. These results are in agreement with a recent analysis by Lion et al. (2016) in a stream of fast wind observed by Wind spacecraft. The authors found the presence of Alfvén vortex-like structures and current sheets, which drastically contributes to the spectral shape of the magnetic field spectrum at ion scales. Furthermore, the comparison of this stream of fast solar wind with the results described in Perrone et al. (2016) in the slow wind context suggests that the latter one is much more complex, with the presence also of strongly compressive structures, such as magnetic holes, solitons, and shocks, with smaller amplitudes with respect to the Alfvénic structures, which propagate in the plasma rest frame.

In a separate study using the MSR technique, Roberts et al. (2017) studied intervals of fast and slow wind plasma. In the fast wind phase speeds were found to be very slow, often below the Alfvén speed, for incompressible and compressible magnetic fluctuations. Meanwhile, in the slow wind the compressible magnetic field showed evidence of fast propagating fluctuations, with some faster than the magnetosonic speed. This is consistent with the results discussed in both Perrone et al. (2016) and the present paper. Therefore, slow solar wind presents a more complex physics with respect to fast wind, where fast structures, moving in the flow, could lead to the generation of some instabilities with additional effects on particles (Papadopoulos 1972).

The difference in the observed families of structures in slow and fast streams fits also into a more general context of the source of these winds (Fieldman et al. 2005). For example, the presence of compressive structures in slow solar wind could be the result of the interaction of the wind with the heliospheric current sheet (Burlaga et al. 2002; Brooks et al. 2015), or could be remnant features of large-scale coronal structures (Wilcox & Ness 1967; McComas et al. 2000). Thanks to Solar Orbiter and Parker Solar Probe, it will be possible to measure the turbulent and structured electric and magnetic fields associated with shocks, reconnection, and stochastic energization in unexplored plasma environments, investigating plasma physics in the source regions of both fast and slow wind. Moreover, Solar Orbiter and Parker Solar Probe will give access to the heliocentric variation of the turbulence, allowing the study of electromagnetic field fluctuations and particle energization processes as a function of radial distance.

Understanding the intermittency phenomenon and the related formation of small-scale coherent nonlinear structures could provide key insights into the general problem of dissipation in collisionless plasma and more particularly in solar wind. The physics of dissipation strongly depends on the different families of structures because of the different physical processes involved in the generation and/or evolution of the considered coherent structures. Our results (in the present paper for fast solar wind and in Perrone et al. (2016) for slow solar wind) show that the vortex-like structures are the dominant form of the observed structures; thus, they may play a major role in the dynamics of the solar wind plasma at ion scales. A very recent theoretical study in nearly incompressible magnetohydrodynamic (NI MHD) turbulence by Zank et al. (2017) has shown that two-dimensional vortex structures are explicitly predicted by the model. In particular, the NI MHD formulation describes the transport of majority 2D and minority slab turbulence throughout the solar wind. This result supports the fact that in both fast and slow solar wind the vortex-like structures are the most frequent intermittent events. It is worth pointing out that the model for NI MHD turbulence deals with the fluid range while the present paper deals with coherent structures at kinetic scales. However, as far as coherent structures cover a very large range of scales, the detected strong events at ion scales show waveforms covering $\sim 30\Delta_{s}$ (the diameter of the vortices). Therefore, the NI MHD turbulence model could still be applicable.

The observed vortices can be divided into two subfamilies with different properties. In particular, we found strongly localized vortices and vortex chains. In the first case, localized vortices could trap particles and, propagating in the flow, could excite density fluctuations and increase heat and mass transport processes. This is the scenario of a strong vortex turbulence (Aburjania et al. 2009). However, these isolated vortices could be the result of merging processes from smaller- to larger-scale structures, such as in the mechanism for self-organization in ideal fluids, creating a finite number of large, well-separated vortices (Novikov & Sedov 1979; McWilliams 1984; Bracco et al. 2000). This phenomenon is called vortex collapse, and
one could expect similar phenomena to occur also in plasmas. For localized structures, as long as the mutual distance between the vortices is larger than their size, there is no interaction between them and they can be described as Alfvén-type vortices (Petrovichvili & Pokhotelev 1992). However, when the vortices are closer together, their shapes start to deform. The vortex merger is an example of interaction where the Alfvén vortex approximation is no longer valid (Schep et al. 1994).

The main idea is that two aligned currents attract each other by the Lorentz force and can then coalesce. The generated vortex pattern has the characteristics of a collision of two vortices and starts to deform the current distribution. Collisionless reconnection of the magnetic field takes place, changing the magnetic topology, and the magnetic flux is converted into electron momentum and ion vorticity, while the magnetic energy is transformed into electron energy (Kuvshinov et al. 1998; Bergmans & Schep 2001).

In the case of fast solar wind, we observed several examples of vortex chains where such interaction can take place, which could be related to a transient state of a collisionless reconnection. If this is the case, magnetic flux could be converted into electron momentum and ion vorticity, while the magnetic energy could be transformed into electron energy (Kuvshinov et al. 1998). Unfortunately, due to very scarce particle measurements at time resolutions comparable to their kinetic scales, the heating process and the complicated phase space interaction in turbulent solar wind still remain a puzzle. In particular, due to the low time resolution of the particle measurements on Cluster, there are not enough points within the structures to study the heating and/or the energization of the particles. Moreover, sometimes the low resolution can generate unphysical effects owing to the procedure of data sampling and averaging (Perrone et al. 2014).

In 2015 March, the Magnetospheric Multiscale (MMS) mission, which consisted of four identically instrumented spacecraft, as well as Cluster, but with a separation of ~10 km, was launched. During phase 2 of the mission, which started in 2017 February, MMS apogee will be raised up to 25R_E and it will spend time in solar wind. In particular, after 2017 September the apogee will be located on the dayside and many intervals of solar wind data will indeed be gathered. In this context, particle distribution functions will be measured with high time resolution (30 ms for electron distributions and 150 ms for ions) and more detailed information will be obtained to better understand the problem of dissipation in such a collisionless plasma.

However, although MMS has improved the temporal resolution for the particle measurements, angular/energy resolution still remains insufficient to completely resolve solar wind ions. A key insight in the study of turbulence, energy dissipation, and particle energization in the near-Earth environment might be provided by the Turbulence Heating Observer (THOR) mission (Vaivads et al. 2016), which is currently in the competitive study phase with two other missions at the ESA and could be selected by the end of 2017. The main goal of this future space mission is to resolve kinetic scale processes, increasing angular and energy resolutions and the sensitivity of instruments, in particular for particle measurements.

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Appendix

Multipoint Signal Resonator Technique

In the present paper we show that the solar wind turbulence is strong with the presence of coherent structures, characterized by coherence (constant phase) over many scales. However, in the context of the solar wind turbulence, many studies have been performed by using the k-filtering technique that was developed for the analysis of multipoint magnetometer data from the Cluster mission (Pinçon & Lefeuvre 1991). The technique requires the assumptions of weak stationarity of the time series and that the signal can be described as a superposition of plane waves with random phases and a small component of isotropic noise. The MSR technique (Narita et al. 2001) is an extension of the k-filtering technique and requires the same assumptions. The main difference is that the MSR technique uses an additional filter based on the Multiple SInal Classification (MUSIC) algorithm (Schmidt 1986), to improve the signal-to-noise ratio of the power spectrum in wavevector space \( P(\omega_\text{sc}, k) \). This method has also been validated for a synthetic signal that consists of random phase plane waves and nonrandom coherent structures (Roberts et al. 2014). Moreover, Roberts et al. (2014) showed that the presence of coherent components in the signal did not affect the recovery of any incoherent components. With the use of this approach, the wavenumber \( k \) with the maximum power in the signal at a given spacecraft frequency \( \omega_\text{sc} \) can be obtained without the need of Taylor’s hypothesis. Moreover, the plasma frame frequency and the phase speed of the fluctuations can be obtained by Doppler-shifting to the plasma frame according to the equations \( \omega_\text{pla} = \omega_\text{sc} - k \cdot v_\text{sw} \) and \( v_\text{ph} = \omega_\text{pla} / k \).

To verify the applicability of the MSR technique on a stream characterized by the presence of coherent structures, where its assumptions are seemingly in contradiction with the idea of strong turbulence, we perform the MSR analysis on this interval of fast solar wind, in two different ways combining data from the four spacecraft. The first is on the three components of the magnetic field, which is dominated by incompressible fluctuations. The second method will focus only on the compressive fluctuations \( \delta B_\perp \) of the magnetic field by using a single input (the magnitude of the magnetic field) at each spacecraft. The application of the method to a single time series at each craft is discussed in detail by Roberts et al. (2017).

It is worth pointing out that this technique has some limitations. First of all, the fluctuations that can be surveyed are limited to scales comparable to the size of the Cluster tetrahedron. The maximum wavenumber is given by the relation \( k_{\text{max}} = \pi / d \), where \( d \) is the mean spacecraft separation (Sahraoui et al. 2010; Roberts et al. 2014). Additionally, the tetrahedron needs to be close to regular such that the spacecraft sample homogeneously in space. In this case planarity and elongation parameters (Robert et al. 1998) are low, \( P \sim E \lesssim 0.15 \), indicating that the geometry is close to that

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of a regular tetrahedron. Moreover, there are two sources of error for the plasma frame speed of the fluctuations. The first one consists in the error on determining the solar wind velocity that dominates the estimation of the plasma frame frequency \( \omega_{pl} \), which is assumed to be 10% (Martz et al. 1993). The second source of error is on the determination of the wavenumber from the method. Sahraoui et al. (2010) demonstrated that for a plane wave the wavenumber is identified with a relative error of 10% at a wavenumber of \( k_{\text{max}} / 25 \), which decreases quickly to 1% at \( k_{\text{max}} \). Furthermore, using the same approach when only a single time series is used at each spacecraft (as is the case when using the \( |B| \) as an input), the errors in determining the wavevector are similar (Roberts et al. 2017).

The results of this analysis, for the considered interval of fast solar wind, are presented in Figure 17, where panels (a), (c), and (e) show the results when applied to the total magnetic fluctuations, while panels (b), (d), and (f) show the results when applied to the fluctuations in the magnitude. It is worth pointing out that, unlike the timing method, where each event is individually analyzed, the MSR technique has a global vision of the whole interval. This not only would include coherent structures but also could contain power from other sources such as incoherent plasma waves. At each frequency the wavevector corresponding to the most energetic fluctuations is recovered; therefore, it is possible that the MSR method gives results exactly for the coherent structures in the paper, but we cannot rule out contributions from other sources. Indeed, the MSR technique shows results similar to the timing method. Both total and compressive fluctuations are characterized by a small phase speed \( (v_{ph} < V_A, V_B) \) and propagation angles almost perpendicular to the global magnetic field \( (\theta_{B0} \sim 90^\circ) \), with \( \theta_{AV} \sim 25^\circ \), even if for the compressive fluctuations a larger spread in both these values is observed. Nevertheless, the fact that \( k \) is quasi-aligned with the solar wind speed could be an effect of the sampling direction. Therefore, it is not possible to conclude on the (non)gyrotropy of the turbulent fluctuations, because no information of the \( k \) perpendicular to the solar wind velocity is known. A numerical study to test this point is needed and will be the subject for a future work.

The results of the MSR technique on the phase speed and propagation angle are consistent with previous cases (Sahraoui et al. 2010; Roberts et al. 2013) and statistical studies (Roberts et al. 2015; Perschke et al. 2016) in the solar wind. This has variously been interpreted as evidence of quasi-linear waves that propagate slowly in the plasma frame (such as the quasi-perpendicular kinetic Alfvén wave; Sahraoui et al. 2010), or coherent structures with \( k_x \approx k_y \) that are advected by the plasma bulk flow, or a combination of these two phenomena (Roberts et al. 2013, 2015). However, in the present work, by looking directly at the magnetic fluctuations around ion scales in the region of high intermittency, it has been clearly shown that the considered time interval is covered by coherent structures (making up \( \sim 30\% \) of the interval). These intermittent structures are characterized by a perpendicular wavevector anisotropy (see the distribution of \( \theta_{B0} \) in Figure 15) and small velocities of propagation in the plasma frame (see Figure 16). Generally, structures that have very weak compressibility such as current sheets and vortices are advected with the flow. Meanwhile, some compressive vortices are measured by the timing method to have higher speed and could account for the larger spread of values seen here.

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