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On the deviation from Maxwellian of the ion velocity distribution functions in the turbulent magnetosheath

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The degree of deviation from the thermodynamic equilibrium in the ion velocity distribution functions (VDFs), measured by the Magnetospheric Multiscale (MMS) mission in the Earth's turbulent magnetosheath, is quantitatively investigated. Taking advantage of MMS ion data, having a resolution never reached before in space missions, and of the comparison with Vlasov-Maxwell simulations, this analysis aims at relating any deviation from Maxwellian equilibrium to typical plasma parameters. Correlations of the non-Maxwellian features with plasma quantities such as electric fields, ion temperature, current density and ion vorticity are very similar in both magnetosheath data and numerical experiments, and suggest that distortions in the ion VDFs occur close to (but not exactly at) peaks in current density and ion temperature. Similar results have also been found during a magnetopause crossing by MMS. This work could help clarifying the origin of distortion of the ion VDFs in space plasmas.

1. Introduction

The interplanetary space is permeated by a plasma in which the effects of particle collisions can be considered negligible. In such a nearly collisionless medium, in the range of scales where kinetic effects dominate the plasma dynamics, the particle velocity

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distribution functions (VDFs) are observed to be far from the thermodynamic equilibrium. Moreover, recent self-consistent numerical simulations and nonlinear models of plasma turbulence dynamics have shown the emergence of significant non-Maxwellian features in the particle VDFs. In particular, 2D-3V (two dimensions in physical space and three dimensions in velocity space) kinetic, hybrid Vlasov-Maxwell (HVM) numerical simulations (Valentini *et al.* 2007), which reproduce the turbulent energy cascade down to ion scales, have highlighted significant local departures of the ion VDFs from a Maxwellian shape close to current sheets, generated by the turbulent cascade and non-uniformly distributed through space, which are often associated with the observed ion temperature anisotropy (Servidio *et al.* 2012; Greco *et al.* 2012). A certain degree of correlation between the emergence of non-Maxwellian features in the ion VDFs and the presence of regions of high ion vorticity has also been found in such simulations (Valentini *et al.* 2016; Sorriso-Valvo *et al.* 2018*b*). Localized heating close to strong enhancements of ion vorticity has also been observed in other numerical experiments (Franci *et al.* 2016; Parashar & Matthaeus 2016). Finally, distortions of the VDFs have been found to be related to strong magnetic field activity and to the magnetic field topology (see Servidio *et al.* (2012)). On the other hand, recent analysis made on solar wind and near-Earth plasma have shown that at proton scales the plasma is characterized by magnetic discontinuities (Retinò *et al.* 2007; Perri *et al.* 2012) that are connected through spatial scales from ion to electron scales (Greco *et al.* 2016; Perrone *et al.* 2016, 2017), giving rise to a complex network, whose effect on the plasma dynamics is still under investigation. Local heating and magnetic energy dissipation at such thin current sheets have been observed in numerical simulations (Wu *et al.* 2013; Perrone *et al.* 2014; Wan *et al.* 2015; Sorriso-Valvo *et al.* 2018*a*). Moreover, very recent works have also found that velocity space fluctuations of the ion VDF are characterized by a broad, power-law Hermite spectrum (that is an enstrophy cascade in the velocity space) both in *in situ* data (Servidio *et al.* 2017) and in numerical simulations (Pezzi *et al.* 2018) and that velocity-space activity is intermittent and concentrated near coherent structures (Pezzi *et al.* 2018).

Thanks to the launch of the Magnetospheric Multiscale (MMS) mission we get both the advantage of very high resolution plasma measurements and the possibility of spatial measurements from a constellation of four identical satellites able to approach a minimum distance close to 7 km. Thus, a big step forward to the understanding of the kinetic physics at both ion and electron discontinuities has been made. Indeed, observations of reconnecting current sheets in the Earth magnetopause have been reported (Burch *et al.* 2016; Ergun *et al.* 2016), as well as signatures of crossings of ion and electron diffusion regions in the Earth magnetosheath (Eriksson *et al.* 2016; Yordanova *et al.* 2016; Vörös *et al.* 2017) and in the magnetopause (Lavraud *et al.* 2016). Those observations clearly show the presence of magnetic energy conversion to plasma heating and to signatures of departure of ion and electron VDFs from the local thermodynamic equilibrium (Graham *et al.* 2017; Sorriso-Valvo *et al.* 2019). Thus, one question can be whether the departure from the Maxwellian equilibrium in a plasma at kinetic scales is statistically significantly related to specific plasma quantities. In order to try to answer such question, here we report a statistical investigation of the correlation between the degree of departure of the ion VDF from a Maxwellian shape and the plasma characteristic parameters, such as temperature anisotropy, current density, and ion vorticity, by comparing MMS data intervals in the Earth's magnetosheath and HVM simulations of turbulence.

2. Magnetosheath event overview and measure of deviation from Maxwellian plasma

In this work, we make use of the high resolution (150 ms) ion VDFs from the Fast Plasma Investigation (FPI) instrument on board MMS (Pollock *et al.* 2016), the magnetic field from the merged fluxgate (FGM) (Russell *et al.* 2016) and the search coil (SCM) data (Le Contel *et al.* 2016), at about 1kHz resolution (Fischer *et al.* 2016), and the electric field data from Electric Double Probes (EDP) instrument, at about 8 kHz sampling rate (Torbert *et al.* 2016; Ergun *et al.* 2016; Lindqvist *et al.* 2016). The data describe a 5 minute period on 2015 November 30 (from 00:21 to 00:26 UT) where the MMS spacecraft were immersed in the quasiparallel turbulent magnetosheath (see Yordanova *et al.* (2016); Vörös *et al.* (2017)). In this interval, the mean magnetic field (averaged over the whole 5 minutes interval) is $B_0 \sim 44$ nT, the ion to electron temperature ratio $T_i/T_e \sim 7$ and the plasma beta (namely the ratio between the plasma kinetic pressure and the magnetic pressure) shows large amplitude fluctuations and is greater than 1. The aim of this work is to investigate the possible presence of non-Maxwellian features in the ion VDFs close to intermittent magnetic structures by means of a parameter that quantifies the deviation of the measured VDF from a Maxwellian shape (Greco *et al.* 2012). Then, these distortions will be compared with the ones observed in numerical experiments of turbulence to shed light on the physical mechanisms that could play a role in this process.

The event overview is shown in figure 1. From top to bottom we have (a) the magnetic field magnitude; (b) the ion bulk speed; (c) the ion density; (d) the ion temperature parallel (black line) and perpendicular (red line) to the mean magnetic field B_0 , (e) the intensity of the current density at 150 ms resolution, computed as $\mathbf{J} = Nq(\mathbf{V}_i - \mathbf{V}_e)$ with N being the plasma density ($N = N_i \sim N_e$); and (f) the $\mathbf{E}' \cdot \mathbf{J}$, which represents the work done by the fields on particles with $\mathbf{E}' = \mathbf{E} + \mathbf{V}_e \times \mathbf{B}$ in the electron frame. All the data is from the MMS1 spacecraft. This represents a sample of turbulent plasma where three thin current sheets encounters have been analyzed in previous studies (Eriksson *et al.* 2016; Yordanova *et al.* 2016; Vörös *et al.* 2017) and are highlighted with colored boxes in figure 1. Thus, in such a turbulent environment the ion VDFs can be highly distorted and modified as observed in numerical simulations (Servidio *et al.* 2012; Perrone *et al.* 2013) and in *in situ* data (Vörös *et al.* 2017; Servidio *et al.* 2017; Sorriso-Valvo *et al.* 2019). An example of one-dimensional VDF cut as a function of energy is shown in figure 2 (symbols), where a clear departure from a Maxwellian distribution (solid line) is observed. Notice that the deviation is highly significant, since the associated noise level in the VDF in the magnetosheath is very low.

In order to quantify the statistical occurrence of deviation from Maxwellian, we make use of the parameter (Greco *et al.* 2012; Valentini *et al.* 2016)

$$\epsilon_i = \frac{1}{n_i} \sqrt{\int (f_i - g_i)^2 d^3v}, \quad (2.1)$$

being n_i the ion density, f_i the observed VDF for the ions, and g_i the equivalent Maxwellian distribution with the same density, temperature, and velocity as the observed one. Thus, $\epsilon_i = 0$ indicates Maxwellian VDF, while any $\epsilon_i \neq 0$ suggests a deviation from the equilibrium. As pointed out in Servidio *et al.* (2017), ϵ_i^2 is related to the phase-space enstrophy. We are comparing the real ion VDFs in the magnetosheath with a Maxwellian distribution as a quantitative measure of distortion of the distributions. We do not actually expect thermodynamic equilibrium in such an environment, so that finding non-Maxwellian distributions is not surprising. For example, the presence of cold

ions (few tens of eV) of ionospheric origin (Toledo-Redondo *et al.* 2016, 2017; Li *et al.* 2017) could also produce a distortion of the ion VDF from a simple Maxwellian. However, the computation of ϵ_i allows us to have a quantitative departure from the Maxwellian equilibrium.

The time series of ϵ_i in our turbulent interval is displayed in the bottom panel in figure 3; notice the burstiness of this quantity with large deviations sparse throughout the whole interval. Besides the time series of ϵ_i , figure 3 shows, from top to bottom, the magnetic field components in the geocentric-solar-ecliptic (GSE) coordinates (B_x -red line; B_y -blue line; B_z -green line) along with the magnitude of the magnetic field (black line), the electric field $E_{\perp} = \sqrt{E_{\perp 1}^2 + E_{\perp 2}^2}$ perpendicular to the local magnetic field (black line)—where $E_{\perp 1}$ lies along $\mathbf{E} \times \mathbf{B}$ and $E_{\perp 2}$ is aligned to $\mathbf{B} \times \mathbf{E} \times \mathbf{B}$ —together with the $|\mathbf{V}_i \times \mathbf{B}|$ (red line), the electric field component parallel to the local mean field, and the ion vorticity $|\omega| = |\nabla \times \mathbf{V}_i|$ from the 4 spacecraft measurements (the inter-satellite distance in this period is about 10 km). Notice that ions are magnetized since E_{\perp} and $|\mathbf{V}_i \times \mathbf{B}|$ track each other very well, and the time series of ϵ_i exhibits features that tend to correlate with E_{\perp} . The two red vertical lines in figure 3 indicate (i) a region where ϵ_i is above a 1σ threshold and seems to be correlated with enhancements in E_{\perp} and $|\omega|$, and (ii) a region (near the right end of the interval) where ϵ_i is closer to zero (below the 1σ). To understand what causes large deviations from Maxwellian in this plasma sample, we have looked at the 2D VDF cuts in the regions indicated by the vertical lines in figure 3.

Figure 4 shows the ion VDFs, plotted in a reference frame with one direction aligned to \mathbf{B} , one direction parallel to $\mathbf{E} \times \mathbf{B}$, and the third perpendicular to both. It is worth stressing that most of the ion VDFs are characterized by a beam-like distribution (mainly along \mathbf{B}), with the beam traveling at about 300 km/s, which is about 3 times the local ion Alfvén speed (Yordanova *et al.* 2016; Sorriso-Valvo *et al.* 2019). Such feature has been found to be frequently present in the peaks of ϵ_i above the threshold (top panels). Figure 4 also shows the 2D VDFs at a time during which ϵ_i is below the threshold (bottom panels). Within the interval, the shape changes abruptly (see also Servidio *et al.* (2017)), with the presence also of a more isotropic distributions. In the process of selecting ion VDFs at the peaks in ϵ_i , we noticed that in several cases the ion VDFs are characterized by several “holes” in different energy channels and look directions, due to absence of detected particles. Such holes would artificially amplify the difference with a Maxwellian distribution. Therefore we take a special care in our analysis and we compute the ϵ_i parameter only when ion VDFs values are fully defined.

3. Comparison between MMS1 data and HVM simulations

In order to investigate the properties of the regions of high deformation for the ion VDFs, we have compared the results coming from the MMS data with those obtained from a numerical simulation of decaying turbulence with guide field for a collisionless plasma in a 2D-3V phase space domain with the HVM code (Valentini *et al.* 2007; Perrone *et al.* 2011). The code solves the Vlasov equation for the ion VDF, while the electrons are considered as an isothermal, massless fluid, and their contribution is taken into account through a generalized Ohms law that retains the Hall term and the electron pressure. The Vlasov equation and the Ohms law are coupled with the Maxwell equations, where the displacement current is neglected. Quasi-neutrality is assumed. The

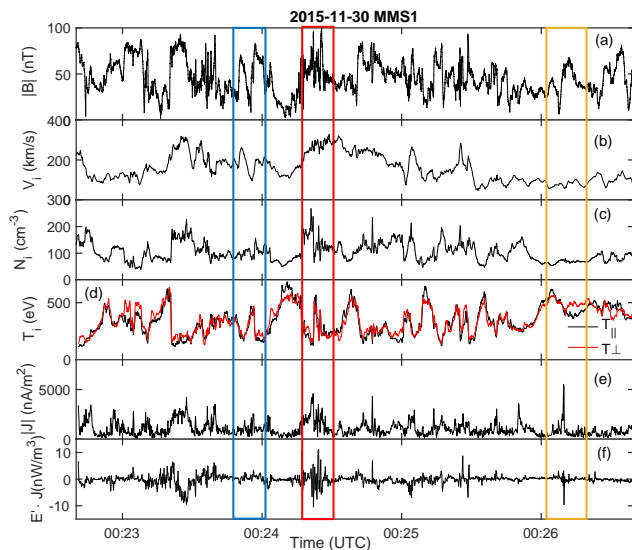


FIGURE 1. From top to bottom: (a) magnetic field magnitude, (b) ion bulk speed, (c) ion density, (d) parallel (black line) and perpendicular (red line) ion temperature, (e) current density magnitude computed using the FPI 150 ms data, (f) $\mathbf{E}' \cdot \mathbf{J}$, being \mathbf{E}' the electric field in the electron rest frame (i.e., $\mathbf{E}' = \mathbf{E} + (\mathbf{V}_e \times \mathbf{B})$) at 150 ms resolution. The color boxes highlight previously reported studies (Eriksson *et al.* 2016; Yordanova *et al.* 2016; Vörös *et al.* 2017).

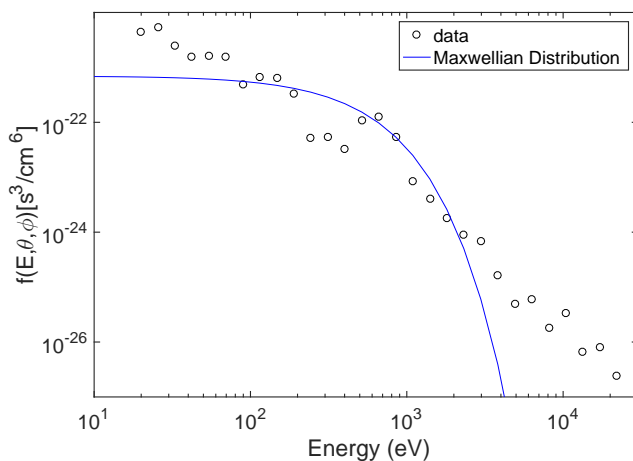


FIGURE 2. Measured ion velocity distribution function (circles) as a function of energy measured at fix angles and at a given time, compared with the associated Maxwellian distribution (solid line).

dimensionless HVM equations can be read as

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{r}} + (\mathbf{E} + \mathbf{v} \times \mathbf{B}) \cdot \frac{\partial f}{\partial \mathbf{v}} = 0 \quad (3.1)$$

$$\mathbf{E} = -\mathbf{u} \times \mathbf{B} + \frac{1}{n} \mathbf{j} \times \mathbf{B} - \frac{1}{n} \nabla p_e + \eta \mathbf{j} \quad (3.2)$$

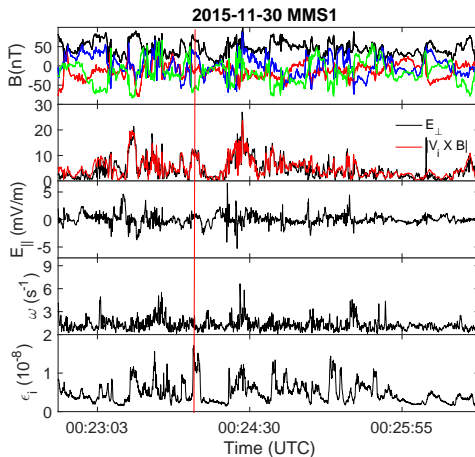


FIGURE 3. From top to bottom: magnetic field components in the GSE reference frame along with the magnetic field intensity (black line); the electric field perpendicular to the local magnetic field direction (black line) along with the intensity of the $\mathbf{V}_i \times \mathbf{B}$ (red line); the electric field component parallel to the local mean field; the ion vorticity; the derived time series of the ϵ_i parameter. The two vertical lines indicate (i) a region with ϵ_i above a 1σ threshold that corresponds also to enhancements in the perpendicular electric field and in the ion vorticity, and (ii) a region of very low ϵ_i .

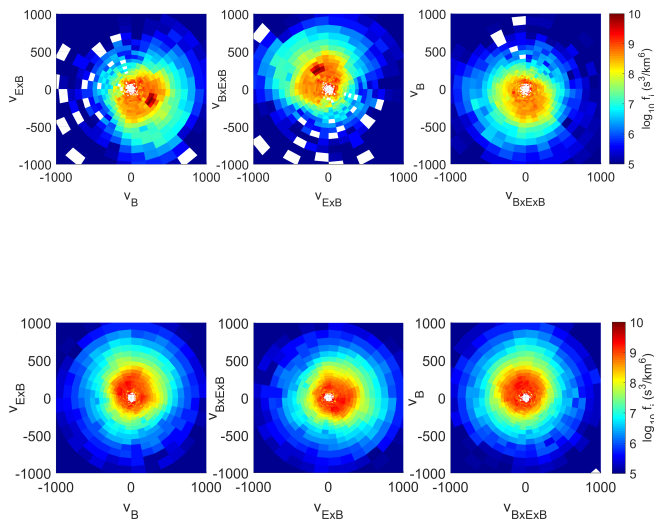


FIGURE 4. 2D VDF cuts in the two regions highlighted with vertical red dashed lines in figure 3. The top panels refer to a peak in ϵ_i , while the bottom panels to a valley in ϵ_i . Notice the presence of a particle beam almost aligned with the \mathbf{B} direction in the top panels.

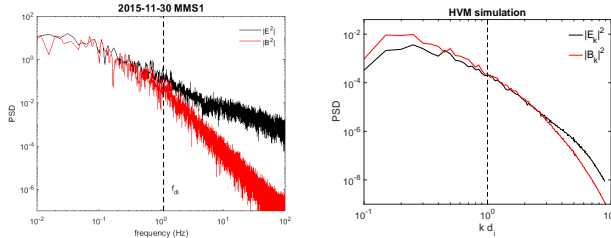


FIGURE 5. Power spectral densities of the normalized electric (black lines) and magnetic (red lines) fluctuations in the MMS1 data set (left panel) and in the HVM simulation (right panel).

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}, \quad (3.3)$$

where $f \equiv f(\mathbf{r}, \mathbf{v}, t)$ is the ion VDF, $\mathbf{E}(\mathbf{r}, t)$ and $\mathbf{B}(\mathbf{r}, t)$ are the electric and the magnetic field, respectively, and $\mathbf{j} = \nabla \times \mathbf{B}$ is the total current density. The ion density, n , and the bulk velocity, \mathbf{u} , are evaluated as velocity moments of the ion VDF. In the above equations, time is scaled by the inverse proton-cyclotron frequency, Ω_{ci}^{-1} , velocity by the Alfvén speed $v_A = B_0/\sqrt{4\pi n_0 m_i}$, lengths by the ion skin depth, $d_i = v_A/\Omega_{ci}$, and masses by the ion mass, m_i . In this paper, the ion distribution function studied from HVM simulations is actually the proton distribution function, so that hereafter when referring to ions, we mean protons in the simulations. At $t=0$, the equilibrium consists of a homogeneous plasma embedded in a uniform background out-of-plane magnetic field, \mathbf{B}_0 , along the z -direction. Ion VDF is initialized with a Maxwellian with homogeneous density. The system evolution is investigated in a double periodic domain (x, y) perpendicular to \mathbf{B}_0 . The equilibrium configuration is perturbed by a 2D spectrum of Fourier modes (Servidio *et al.* 2012; Perrone *et al.* 2013; Valentini *et al.* 2014, 2016). The root mean square of the magnetic perturbations is $\delta b/B_0 \sim 0.3$ and neither density disturbances nor parallel fluctuations are imposed at $t = 0$. The plasma beta is $\beta = 2v_{th,i}^2/v_A^2 = 0.5$, where $v_{th,i} = \sqrt{T_i/m_i}$ is the ion thermal speed. The ion to electron temperature ratio is $T_i/T_e = 1$. Finally, the system size in the spatial domain is $L = 2\pi \times 20d_i$ in both x and y directions, discretized with 512^2 grid-points, while the 3D velocity domain, limited by $\pm 5v_{th,i}$ in each directions, is discretized with an uniform grid of 71^3 points.

The omni-directional electric and magnetic field power spectral densities in the simulations are displayed in the right panel of Figure 5 at the maximum of the turbulent activity. At sub-ion scales, the turbulence becomes dominated by the electric fluctuations. The same trend has also been found in the MMS1 data (see left panel in Figure 5), where the trace of the power spectral densities of the normalized electric $(E^2/(v_A B_0)^2)$ and magnetic $((B/B_0)^2)$ fluctuations are shown. Indeed, at the frequency corresponding at the ion skin depth in the data interval (vertical dashed line in the left panel in 5), the normalized electric field fluctuations have a power higher than the one stored in the magnetic field fluctuations.

Figure 6 shows an overview of the numerical results, in the same format as figure 3. These physical quantities have been tracked along a one-dimensional cut of the 2-D spatial domain of the simulation, i.e. a diagonal path s , normalized to d_i , that crosses the simulation box several times. In the simulation, like in the MMS data, protons are magnetized and ϵ_p is burst-like. To make a comparison with the VDFs observed by MMS1, we have selected a small portion of the signal where peaks in ϵ_p , ω , and E_\perp occur almost simultaneously (i.e., at $s/d_i = 1324$, indicated by the vertical line in figure 6) and we have checked the shape of the ion VDF. In figure 7, we plot the 2D cuts of the ion VDF, where the v_z component is parallel to the background magnetic field direction. While in

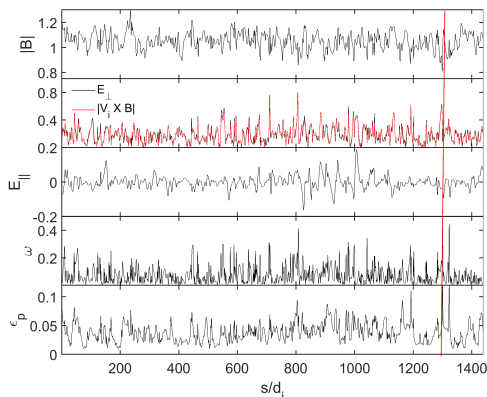


FIGURE 6. Same format as figure 3. The time series are measured along a one-dimensional cut in the HVM box. The vertical line indicates a region of high vorticity, large value of ϵ_p , and high perpendicular electric field.

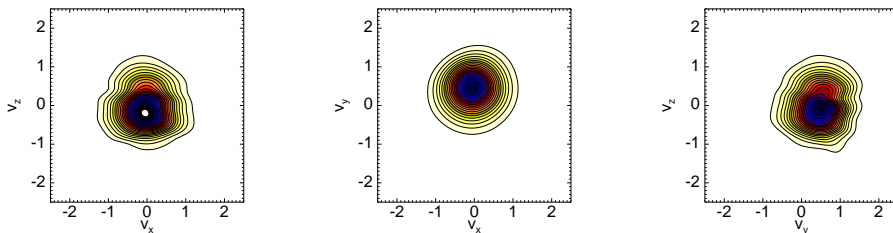


FIGURE 7. 2D VDF cuts in the portion of the signal highlighted in figure 6 by the vertical dashed line. A beam almost aligned with the \mathbf{B}_0 direction is clearly visible.

the plane perpendicular to \mathbf{B}_0 the VDF is almost isotropic, with a shift towards positive values of v_y due to large scale fluctuations, in the other two planes a beam nearly aligned with \mathbf{B}_0 is evident, a feature similar to the one observed in the top panels of figure 4. Thus, the presence of high vorticity regions, with enhanced perpendicular electric fields, exhibit distorted ion VDFs with the formation of a beam travelling along \mathbf{B}_0 at almost the Alfvén speed (Sorriso-Valvo *et al.* 2019).

As noticed in figure 3, the time series of the ϵ_i parameter computed with the MMS1 data has some features that can also be recognized in the time series of other quantities, such as the perpendicular component of the electric field and the ion vorticity. In order to highlight such similarities, we have generated scatter plots of ϵ_i as a function of different quantities, in order to investigate the physical quantities that might correlate with distortions in the ion VDFs (both in the data and in the simulations). Figure 8 shows the scatter plots of ϵ_i versus the intensity of the electric field in the plasma frame, namely $\mathbf{E}' = \mathbf{E} + (\mathbf{V}_i \times \mathbf{B})$ degraded to 0.15 sec resolution in the magnetosheath interval (left panel) and in the HVM simulation (right panel). The Pearson correlation coefficient is also reported in the panels, indicating a very good degree of correlation in the MMS1 data set. Of course, since the region is highly turbulent both the fields and the plasma quantities display considerably fluctuations, giving rise to a certain degree of dispersion in the scatter plots. Thus, we have overplotted the ϵ_i parameter mean values within bins

of the electric field (red squares in figure 8). This procedure highlights the correlation between the two quantities. Besides the good degree of correlation with the intensity of the electric field, the ϵ_i parameter tends to be linearly correlated with magnetic field fluctuations $\delta B/B_0$ (see figure 9) both in the data and in the simulation. This confirms that high distortions in the ion VDFs can occur within regions of strong magnetic activity (Servidio *et al.* 2012). On the other hand, figure 10 displays a scatter plot of ϵ_i with the magnitude of the current density (see Section 2) for the magnetosheath data (left panel) and for the HVM simulation (right panel). The Pearson correlation is < 0.2 in both cases and very weak correlation can be noticed from observing the the average ϵ_i values (red squares). Notice that Valentini *et al.* (2016) have pointed out that in the simulations the deviation from the Maxwellian equilibrium is non-homogeneous in space and tends to be maximized around the peaks of the current density that naturally form at the interfaces of magnetic flux tubes. Thus, the good match between data and simulation in figure 10 suggests that a similar scenario can be envisaged in the turbulent magnetosheath interval. Besides the current density, the correlation between the ion vorticity, as computed with a multi-spacecraft technique in the MMS data (see Section 2), and ϵ_i has been studied both in the data and in the simulation. The scatter plots are given in figure 11. In such case, the correlation in the data is poor (0.13) although the average of ϵ_i in bins of $|\omega_i|$ shows a certain degree of correlation, while it is higher in the HVM simulations where the formation of vortices tends to distort the ion VDFs. However, a closer look at figure 3 points out that some peaks in ϵ_i occur during peaks in the ion vorticity, although the great variability of all those quantities at very short time scales makes the correlation analysis complex. ϵ_i does not seem to correlate neither with ion temperature (not shown) nor with the temperature anisotropy (see figure 12) both in the data and in the simulation, as well as with the magnetic energy conversion/dissipation computed via $\mathbf{E}' \cdot \mathbf{J}$ (not shown). The fact that there is no evident correlation between ϵ_i and the temperature anisotropy, which intrinsically is a deviation from the thermodynamic equilibrium, suggests the emergence of a very complex scenario in the process of the turbulent energy transfer at ion and sub-ion scales related to phase-space structures that cannot be described in terms of pressure tensor anisotropy (Chew *et al.* 1956).

The turbulent activity produces distortions of the VDFs that are much more complex than the generation of temperature anisotropy, thus hiding the natural correlation between ϵ_i and T_{\parallel}/T_{\perp} . Here, the ion agyrotropy of the pressure tensor, namely the departure of the pressure tensor from cylindrical symmetry about the local mean field, has been calculated by using the expression of Swisdak (2016)

$$Q = 1 - \frac{4l_2}{(l_1 - P_{\parallel})(l_1 + 3P_{\parallel})}, \quad (3.4)$$

where $P_{\parallel} = b_x^2 P_{xx} + b_y^2 P_{yy} + b_z^2 P_{zz} + 2(b_x b_y P_{xy} + b_x b_z P_{xz} + b_y b_z P_{yz})$, l_1 is the trace of the pressure tensor and $l_2 = P_{xx} P_{yy} + P_{xx} P_{zz} + P_{yy} P_{zz} - (P_{xy} P_{yx} + P_{xz} P_{zx} + P_{yz} P_{zy})$. The correlation with ϵ_i is plotted in figure 13 and by definition $Q = 0$ indicates gyrotropy. In the HVM simulation, the agyrotropy of the ion pressure tensor is well correlated with the deviation from Maxwellian. Thus, highly distorted ion VDFs have high probability to be associated with large agyrotropy. This is not really surprising since the latter can be seen as a deviation from Maxwellian. On the other hand, the correlation in the MMS1 data (left panel in figure 13) is much weaker than the one observed in the simulations, although again a certain linear trend can be recognized.

Finally, the degree of correlation between ϵ_i and the plasma β in the MMS1 data set has been studied. The plasma beta varies over a broad range of values and tends to be greater than 1. Thus, we have reported in figure 14 the scatter plot in log-log axis

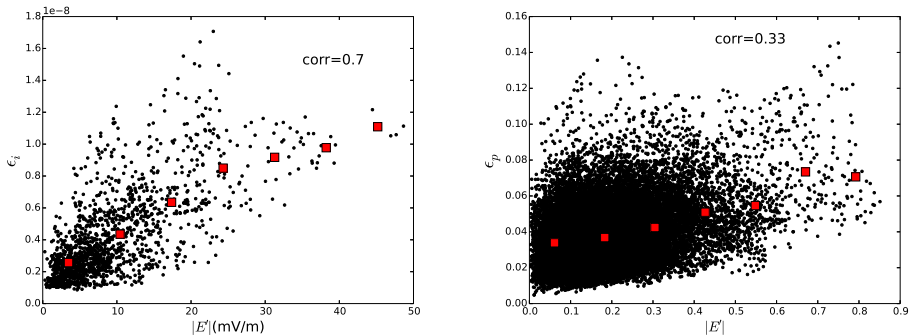


FIGURE 8. The ϵ_i parameter as a function of the magnitude of the electric field in the plasma frame in the MMS data (left panel), and in the HVM simulation (right panel). The electric field data in the magnetosheath have been averaged out to 0.15 sec resolution. The Pearson correlation indices are indicated in the panels. Red squares report the mean values of ϵ_i within bins of $|E'|$.

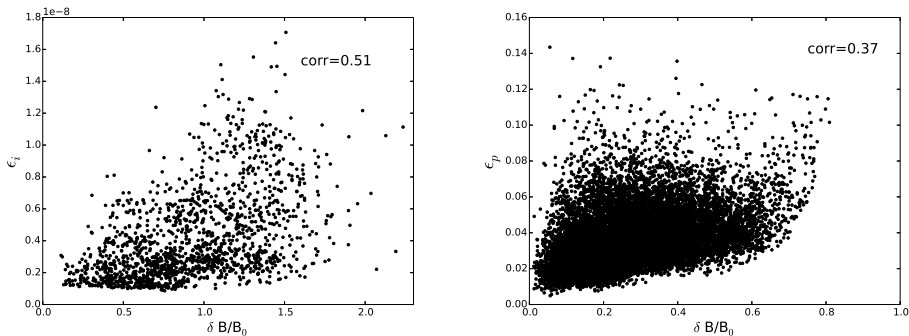


FIGURE 9. Same format as figure 8 for the ϵ_i parameter as a function of the magnetic field fluctuations. Notice the good correlation both in the MMS data and in the numerical experiment.

between ϵ_i and β : a good anticorrelation can be recognized (with a Spearman correlation coefficient ~ -0.6). In this case, since the range of variation of β is pretty large, the linear Pearson correlation is much lower than the Spearman. The largest deviations from Maxwellian clusterize around $\beta < 3$, that is when the thermal speed of ions tends to be of the same order of the Alfvén speed. In such a case, all the fluctuations that propagate at v_A interact with the bulk of the ion VDF, inducing distortion in the distribution function.

4. Discussions

The highly turbulent medium downstream of the quasi-parallel bow shock, as observed by the MMS spacecraft, shows a very bursty behavior in both magnetic field and plasma data. The parameter ϵ_i , which quantifies the degree of deviation of the ion VDFs from a Maxwellian shape, has been computed throughout the 5 minute interval analyzed, showing again high variability, with regions of strong departure of VDFs from thermodynamic equilibrium. Such a great variability makes the analysis of the correlation between ϵ_i and physical quantities, such as temperature anisotropy, current density, ion vorticity, very complex. A comparison between MMS1 data and results coming from a HVM simulation has been performed. The comparison highlights a certain degree

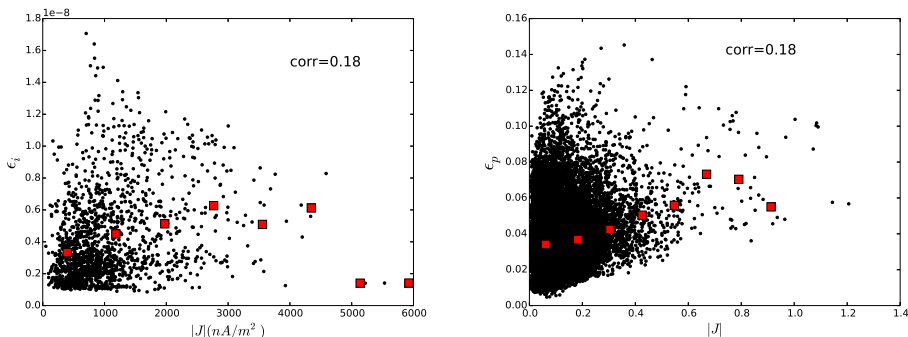


FIGURE 10. Same as figure 8 for the ϵ_i parameter as a function of the current density magnitude.

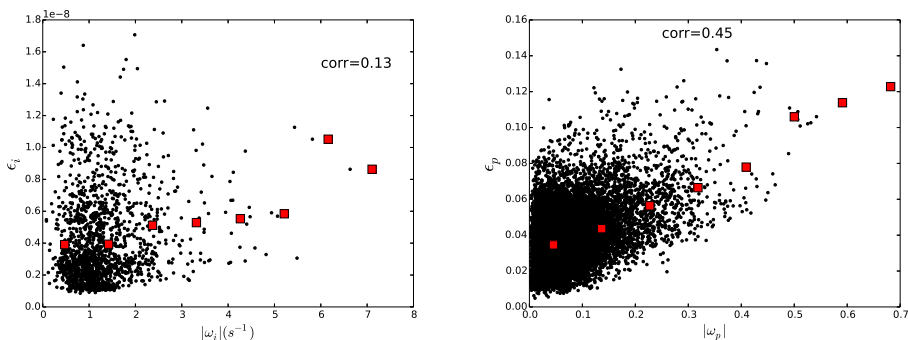


FIGURE 11. Same format as figure 8 for the ϵ_i parameter as a function of the magnitude of the ion vorticity.

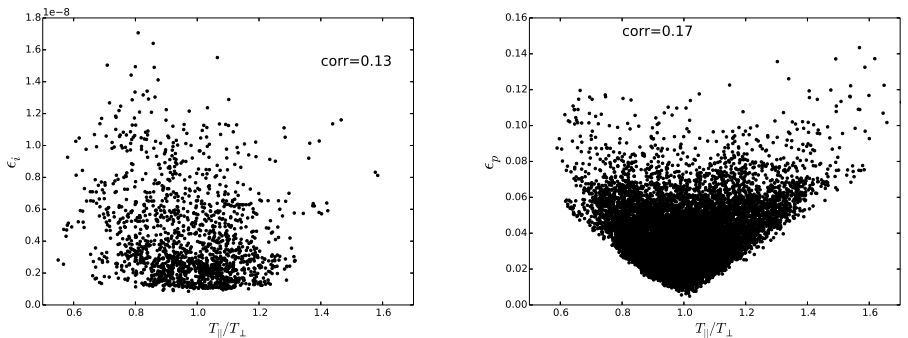


FIGURE 12. Same as figure 8 for the ϵ_i parameter as a function of the temperature anisotropy.

of correlation between peaks in the ϵ_i (high deviation from a Maxwellian shape) and the presence of high current density (thin current sheets) regions. However, no clear correlation has been found with temperature anisotropy (calculated with respect to the local magnetic field) and with the magnetic energy conversion/dissipation (taken as $\mathbf{E}' \cdot \mathbf{J}$) both in the data and in the simulations. Similar results (not shown) have also been found in a MMS data set on 8 September 2015, when the spacecraft was located in the dusk-side magnetopause, moving towards the magnetosheath (Stawarz *et al.* 2016).

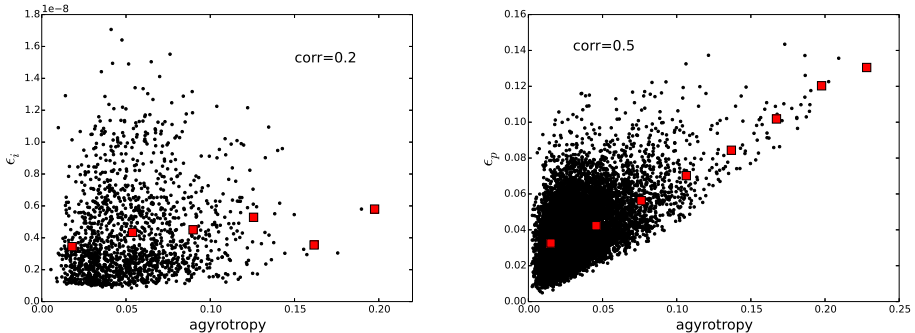


FIGURE 13. Same format as figure 8 for the ϵ_i parameter as a function of the agyrotropy of the pressure tensor (see text).

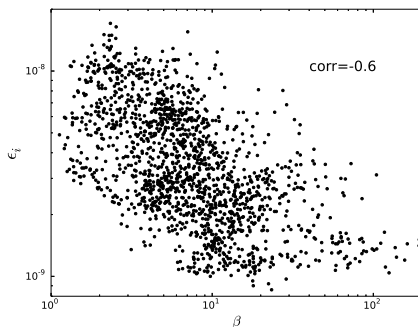


FIGURE 14. Scatter plot in log-log axes of the ϵ_i parameter as a function of the plasma beta in the MMS1 data set. A clear anticorrelation (computed using the Spearman correlation) has been found.

The correlation between ϵ_i and the ion temperature is rather complex. Indeed, a more in-depth analysis gives indication of a temperature increase in the vicinity of large amplitude peaks in epsilon (selected, for example, via a threshold method), but not at the peaks. This would justify a more pronounced anticorrelation observed in the data (not shown). Numerical simulations also exhibit no correlation between distortion of the proton VDF and proton temperature. Recently, Chasapis *et al.* (2018) have shown a strong parallel electron heating at regions of high current density also associated to distortion of the electron VDFs. The analysis carried out on the ions shows that the presence of localized regions of high current density and strong energy dissipation (by means of $\mathbf{E}' \cdot \mathbf{J}$) weakly influences the shape of the particle distribution functions, as also displayed in numerical experiments (Valentini *et al.* 2016; Sorriso-Valvo *et al.* 2018b), thus making complex and challenging the determination of the origin of non-Maxwellianity of ion VDFs in collisionless plasmas (Sorriso-Valvo *et al.* 2019). On the other hand, there is a clear tendency to develop non gyrotropic features close to velocity gradients in the plasma (Franci *et al.* 2016; Parashar & Matthaeus 2016; Valentini *et al.* 2016; Sorriso-Valvo *et al.* 2018b), probably due to a shear-induced anisotropization mechanism (Del Sarto *et al.* 2016; Del Sarto & Pegoraro 2018), within regions with $\beta \sim 1$, where the interaction between the bulk of the ion VDF and the fluctuations propagating at v_A is maximized, and close to strong bursts of perpendicular electric field, being ions highly magnetized (Sorriso-Valvo *et al.* 2019). It is worth stressing that at sub-ion scales

the energy stored in the electric fluctuations is higher than that contained in the magnetic field fluctuations. This evidence, together with the observation of a correlation between ϵ_i and the electric field in the plasma frame, suggests that the nature of the distortion of ion VDFs can be electrostatic. However, this aspect needs further investigation and opens to the possibility to a strong interaction between particles and almost electrostatic waves, propagating along the mean magnetic field, at sub-ion scales, as a mechanism for the energy cascade towards the electron scales.

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