

## VLASOV SIMULATIONS OF MULTI-ION PLASMA TURBULENCE IN THE SOLAR WIND

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### ABSTRACT

Hybrid Vlasov-Maxwell simulations are employed to investigate the role of kinetic effects in a two-dimensional turbulent multi-ion plasma, composed of protons, alpha particles and fluid electrons. In the typical conditions of the solar-wind environment, and in situations of decaying turbulence, the numerical results show that the velocity distribution functions of both ion species depart from the typical configuration of thermal equilibrium. These non-Maxwellian features are quantified through the statistical analysis of the temperature anisotropy, for both protons and alpha particles, in the reference frame given by the local magnetic field. Anisotropy is found to be higher in regions of high magnetic stress. Both ion species manifest a preferentially perpendicular heating, although the anisotropy is more pronounced for the alpha particles, according with solar wind observations. Anisotropy of the alpha particle, moreover, is correlated to the proton anisotropy, and also depends on the local differential flow between the two species. Evident distortions of the particle distribution functions are present, with the production of bumps along the direction of the local magnetic field. The physical phenomenology recovered in these numerical simulations reproduces very common measurements in the turbulent solar wind, suggesting that the multi-ion Vlasov model constitutes a valid approach to the understanding of the nature of complex kinetic effects in astrophysical plasmas.

### 1. INTRODUCTION

Astrophysical plasmas are generally in a fully turbulent regime. In particular, the solar wind can be considered as a natural laboratory for studying physical processes of plasma turbulence, whose dynamic scales cannot be achieved in laboratory experiments. Collisions in the solar wind are very rare: the particle mean free path is comparable to (or larger than) the system size ( $\simeq 1$  AU). These properties suggest that small-scale mechanisms should be more complex than one would expect from a fluid (viscous) description.

Spacecraft measurements generally reveal that the electromagnetic field fluctuations in the solar wind are in a state of fully-developed turbulence (Bruno & Carbone 2005; Marsch 2006). The power spectrum of the fluctuating fields manifests a behavior reminiscent of the  $k^{-5/3}$  power-law for fluid turbulence (Kolmogorov 1941), where  $k$  here is the wavenumber obtained applying the Taylor hypothesis. This inertial range turbulence extends to smaller spatial scales down to a range of wavelengths where kinetic effects dominate the plasma dynamics. At these scales, different physical processes come into play, leading to spectral shape changes. The first clear spectral change appears at scales such as the ion inertial length and/or the ion Larmor radius (Leamon et al. 2000; Bourouaine et al. 2012; Bale et al. 2005), where the spectrum of the magnetic field gets steeper (Bale et al. 2005). At the range of spatial lengths of the order of the electron kinetic scales the interpretation of the solar-wind observations is still controversial. Two different scenarios have been recently pictured: a second spectral break with an additional power-law range (Sahraoui et al. 2010) and an exponential cut-off (Alexandrova et al. 2009) that instead marks the end of self-similarity. In both cases, a theoretical support from

self-consistent, fully nonlinear, Vlasov models is needed for the interpretation of this complex phenomenology.

This general picture of astrophysical turbulence becomes more complicated because of the multi-component nature of the solar wind. The interplanetary medium, although predominantly constituted of protons, is also made of a finite amount of doubly ionized helium (alpha particles), together with a few percentage of heavier ions. Several observations (Marsch et al. 1982a,b; Kasper et al. 2008) have shown that heavier ions are heated and accelerated preferentially as compared to protons and electrons. Moreover, in recent analysis performed on solar-wind data from the Helios spacecraft, the link between the signatures of kinetic effects and some important parameters of heavy ions, such as relative speed, temperature ratio and anisotropy, has been investigated (Bourouaine et al. 2010, 2011a,b). In these works the authors pointed out that more significant anisotropies and non-Maxwellian features are detected for alpha particles distribution functions with respect to protons. The evolution of the velocity distribution functions in the solar wind, and the production of kinetic signatures such as heating and temperature anisotropies represent nowadays some of the key issues of plasma physics (Osman et al. 2011, 2012).

The two points discussed above, that the kinetic scales have a determinant effect in shaping the turbulent spectra and that the role of secondary ions cannot be neglected, suggest that a multi-scale and multi-species self-consistent Vlasov treatment of the turbulent solar wind is required. The detection of the main kinetic processes that, acting on small scales, are responsible for the energy dissipation and the heating production, represents today one of the main challenges for the plasma scientific community. A kinetic description of collisionless plasma turbulence offers the powerful opportunity of giving im-

portant insights for the interpretation of “in situ” satellite measurements in the solar wind. In this context, an indispensable and crucial support to investigate the complexity of solar-wind physics is represented by kinetic numerical simulations.

The most widely adopted numerical description of the kinetic plasma physics is represented by the Particle in Cell (PIC) methods. The Lagrangian PIC approach is based on the integration of the equations of motion of a large number of macro-particles under the effects of self-consistent electromagnetic fields. The PIC simulations have been extensively used for the description of the kinetic dynamics of space plasmas, addressing the problem of wave-particle interaction (Araneda et al. 2008), particle heating (Araneda et al. 2009) and turbulence (Gary et al. 2008; Saito et al. 2008; Parashar et al. 2010; Camporeale & Burgess 2011; Parashar et al. 2011; Markovskii & Vasquez 2002). Nowadays, thanks to the fast technological development of the computational resources, the Eulerian approach for the numerical solution of the Vlasov equation has become accessible as an alternative to the PIC approach (Mangeney et al. 2002). The Eulerian Vlasov simulations, in which the time evolution of the particle distribution function is followed numerically in a discretized phase space domain, are significantly more demanding from the computational point of view compared to the PIC simulations. Nevertheless, at variance with the PIC methods, the Vlasov algorithms are mostly noise-free and do not introduce additional (unphysical) heating due to the particle noise. This point can be crucial when dealing with the numerical description of the short wavelengths part of the turbulent cascade, where the energy level of the fluctuations is typically very low and the statistical noise introduced by the PIC calculations can possibly cover the physical information.

Recently (Mangeney et al. 2002; Valentini et al. 2005, 2007), an Eulerian hybrid Vlasov-Maxwell code (HVM hereafter) has been developed. This algorithm integrates numerically the Vlasov equation in phase space coupled to the Maxwell equations for the electromagnetic fields. The Vlasov equation is solved for the proton species, while electrons are treated as a fluid (Valentini et al. 2007). The HVM code has been extensively used for the analysis of the kinetic effects during the evolution of the solar-wind cascade (Valentini et al. 2008; Valentini & Veltri 2009; Valentini et al. 2010, 2011). Furthermore, Servidio et al. (2012) made use of the HVM algorithm to investigate the role of local kinetic effects in plasma turbulence in a 2D-3V phase space configuration (two dimensions in physical space, and three in velocity space). It has been shown that, nearby the region of strong magnetic activity, the proton distribution function is deformed by kinetic effects displaying significant non-Maxwellian features. Moreover, in these regions characterized by high magnetic stress, reconnection events can occur locally, as it has been also described in both PIC and Magnetohydrodynamic simulations (Servidio et al. 2009; Drake et al. 2010).

As discussed previously, in the solar wind description it is important to take account of its multi-component nature. For this purpose, Perrone et al. (2011) have proposed an update version of the HVM code, which includes the kinetic dynamics of heavy ions. In particular,

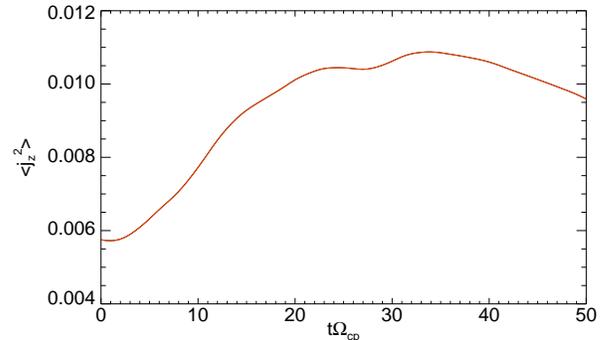


FIG. 1.— Time evolution of the average out-of-plane squared current density  $\langle j_z^2 \rangle$ .

the authors examined the effects produced by the presence of alpha particles in the evolution of the solar-wind turbulent cascade in the direction parallel to the ambient magnetic field in a 1D-3V phase space configuration.

In the present paper we discuss the results obtained by the “multi-component” version of the HVM code in a 2D-3V phase space configuration. In order to study the turbulent activity in the presence of alpha particles, we adopt an approach similar to the one used by Servidio et al. (2012), extending the above results to the more realistic multi-ion treatment. As we will discuss in the following, our numerical simulations reproduce several features commonly observed in space plasmas. As the result of the turbulent cascade, coherent structures appear in the system, with regions of high magnetic stress where reconnection locally occurs; in correspondence of these regions the particle distribution functions are heavily distorted, exhibiting a significant temperature anisotropy. This effect is more evident for alpha particles than for protons, consistent with recent observations in the solar wind (Bourouaine et al. 2010, 2011b).

## 2. NUMERICAL MODEL

We simulate a collisionless and magnetized multi-species (electrons, protons and alpha particles) turbulent plasma through the use of the HVM code. Within this HVM model, the Vlasov equation for proton ( $f_p$ ) and alpha particle ( $f_\alpha$ ) distribution functions (Valentini et al. 2007; Perrone et al. 2011) is integrated numerically in a 2D-3V phase space domain. Electrons are treated as a fluid and a generalized Ohm equation, where a resistive term has been added as a standard numerical Laplacian dissipation, is considered. The dimensionless HVM equations are given by

$$\frac{\partial f_i}{\partial t} + \mathbf{v} \cdot \frac{\partial f_i}{\partial \mathbf{r}} + (\mathbf{E} + \mathbf{v} \times \mathbf{B}) \cdot \frac{\partial f_i}{\partial \mathbf{v}} = 0, \quad (1)$$

$$\mathbf{E} = -(\mathbf{u}_e \times \mathbf{B}) - \frac{1}{n_e} \nabla P_e + \eta \mathbf{j}, \quad (2)$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}. \quad (3)$$

The quasi-neutrality approximation  $n_e = \sum_i Z_i n_i$  is considered, where  $n_e$  and  $n_i$  are the electron and ion densities respectively and  $Z_i$  the ion charge number (the subscript  $i = p, \alpha$  stands for protons and alpha particles respectively). In Eq. (1),  $f_i(\mathbf{r}, \mathbf{v}, t)$  is the ion distribution function,  $\mathbf{E}(\mathbf{r}, t)$  and  $\mathbf{B}(\mathbf{r}, t)$  are the electric and magnetic

fields. In Eq. (2), the electron bulk velocity is defined as  $\mathbf{u}_e = (\sum_i Z_i n_i \mathbf{u}_i - \nabla \times \mathbf{B})/n_e$ , where the ion bulk velocities  $\mathbf{u}_i$  are evaluated as first order velocity moments of the ion distribution function; finally,  $\mathbf{j} = \nabla \times \mathbf{B}$  represents the total current density. An isothermal equation of state for the electron pressure  $P_e$  closes the system.

In Eqs. (1)-(3) time is scaled by the inverse proton-cyclotron frequency  $\Omega_{cp}^{-1}$ , velocities by the Alfvén speed  $V_A$ , lengths by the proton skin depth  $d_p = V_A/\Omega_{cp}$  and masses by the proton mass  $m_p$ . From now on, all the physical quantities will be expressed in units of the characteristic parameters listed above. A small value for the resistivity ( $\eta = 2 \times 10^{-2}$ ) has been chosen in order to achieve relatively high Reynolds numbers and to remove any spurious numerical effects due to the presence of strong current sheets. The initial equilibrium consists of a plasma composed of kinetic protons and alpha particles, with Maxwellian velocity distributions and homogeneous densities ( $n_{0,p}$  and  $n_{0,\alpha}$  respectively), and fluid electrons embedded in a background magnetic field  $\mathbf{B}_0 = B_0 \mathbf{e}_z$ . The plasma dynamics and the development of turbulence are investigated in a double periodic ( $x, y$ ) domain perpendicular to  $\mathbf{B}_0$ , where the total magnetic field can be written as  $\mathbf{B} = \mathbf{B}_0 + \mathbf{B}_\perp$ .

The equilibrium configuration is perturbed by a 2D spectrum of fluctuations for the magnetic and proton velocity fields (alpha particles have zero initial bulk velocity). We inject energy with random phases and wave numbers in the range  $0.066 < k < 2$ , where  $k = 2\pi m/L$ , with  $2 \leq m \leq 6$  and  $L$  being the box size in each spatial direction. The rms of the initial magnetic perturbations is  $\delta B/B_0 \simeq 0.3$ . Neither density disturbances nor parallel variances are imposed at  $t = 0$ . The proton plasma beta is  $\beta_p = 2v_{th,p}^2/V_A^2 = 2$  (where  $v_{th,p} = \sqrt{T_p/m_p} = 1$  is the proton thermal speed) and the electron to proton temperature ratio is  $T_e/T_p = 1$ . For the alpha particles we set  $Z_\alpha = 2$ ;  $m_\alpha/m_p = 4$ ,  $n_{0,\alpha}/n_{0,p} = 5\%$  and  $T_\alpha/T_p = 1$ . With this choice, the alpha particle thermal speed is  $v_{th,\alpha} = v_{th,p}/2$ .

The system size in the spatial domain is  $L = 2\pi \times 20d_p$  in both  $x$  and  $y$  directions, while the limits of the velocity domain for both ion species are fixed at  $v_{max,i} = \pm 5v_{th,i}$  in each velocity direction. In these simulations, we use  $512^2$  grid-points in the two-dimensional spatial domain and  $61^3$  and  $31^3$  grid-points in proton and alpha particle three-dimensional velocity domains, respectively. We point out that in the Ohm equation for the electric field we have neglected the electron inertia terms. These terms are in fact proportional to the squared electron skin depth (which in scaled units is given by  $d_e^2 = m_e/m_p$ ), then cannot be adequately resolved within the discretization of our simulations. The time step  $\Delta t$  has been chosen in such a way that the Courant-Friedrichs-Lewy condition for the numerical stability of the Vlasov algorithm is satisfied (Peyret & Taylor 1986).

### 3. NUMERICAL RESULTS

We numerically study the kinetic evolution of protons and alpha particles in a situation of decaying turbulence. We expect that kinetic effects develop simultaneously with magnetic fluctuations and shears, the latter playing a fundamental role in the production of interesting features such as particle acceleration, heating, tempera-

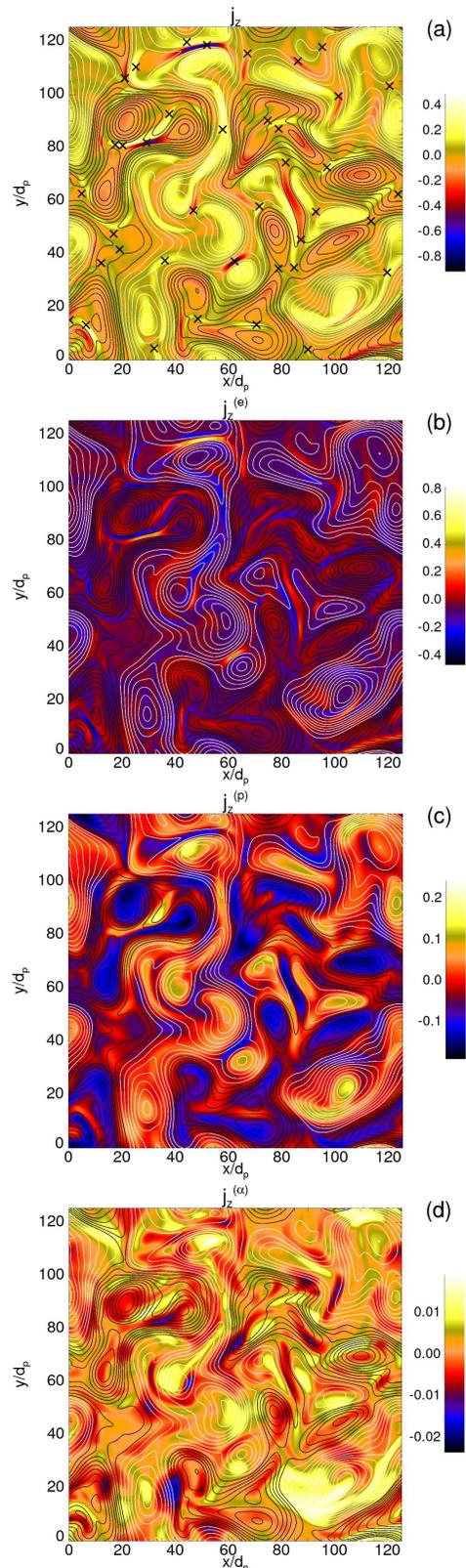


FIG. 2.— Contour plots (shaded colors) of the out-of plane current densities:  $j_z$  (a),  $j_z^{(e)}$  (b),  $j_z^{(p)}$  (c), and  $j_z^{(\alpha)}$  (d). The isolines of the magnetic potential  $A_z$  are indicated by black/white lines. In panel (a), the positions of the X-points (regions of magnetic reconnection) are indicated by black thick crosses.

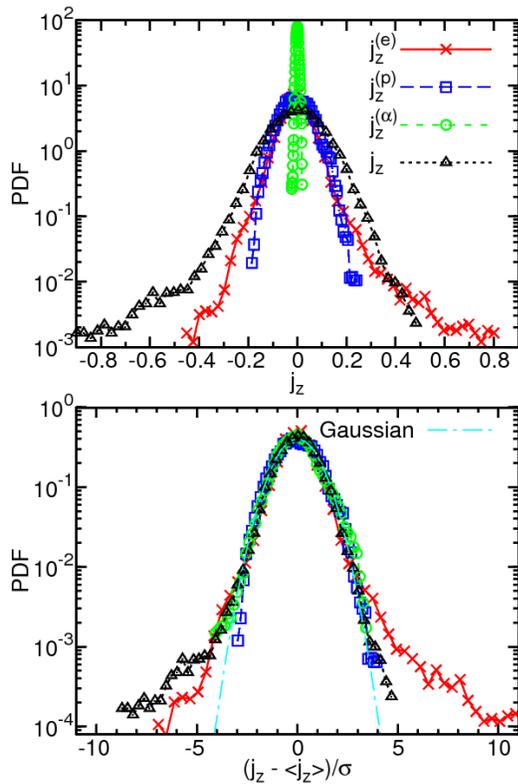


FIG. 3.— In the top panel we show the PDFs of the different current densities:  $j_z^{(e)}$  red solid-cross line,  $j_z^{(p)}$  blue dashed-square line,  $j_z^{(\alpha)}$  green dashed-circle line, and  $j_z$  black dashed-triangle line. In the bottom panel, the PDFs of the standardized variables, obtained by subtracting the average and normalizing to the respective rms value, are reported. The light-blue dot-dashed line is the Gaussian fit.

ture anisotropy, wave-particle like interactions, and generation of beams in the ion distribution function.

As in the fluid counterpart, large scale fluctuations produce a turbulent cascade toward small scales (high  $k$ 's). In analogy with fluid models (MHD, Hall MHD, etc.) of decaying turbulence (Mininni & Pouquet 2009), it is possible to identify an instant of time at which the turbulent activity reaches its maximum value. Since the current density is proportional to the level of small-scale gradients, a good indicator of the level of turbulent activity is represented by the average out-of-plane squared current density  $\langle j_z^2 \rangle$ , whose time evolution is shown in Figure 1. Evidently, at  $t = t^* \sim 40$   $\langle j_z^2 \rangle$  attains its maximum value. This is the characteristic time at which decaying turbulence shares many statistical similarities with steady state (driven) turbulence, and, at this time, we perform our analysis.

The turbulent activity leads to the generation of coherent structures. Vortices and current sheets appear in the contour plots of Figure 2, where shaded contours of the out-of-plane total current density  $j_z$  [panel (a)] are represented. In the same figure, for the descending panels, the separate contributions  $j_z^{(i)}$  of each species, namely  $j_z^e$  (electron current),  $j_z^p$  (proton current), and  $j_z^\alpha$  (alpha-particle current) are also shown. The contour lines in each plot represent the magnetic potential  $A_z$  of the inplane magnetic field ( $\mathbf{B}_\perp = \nabla A_z \times \mathbf{e}_z$ ). The

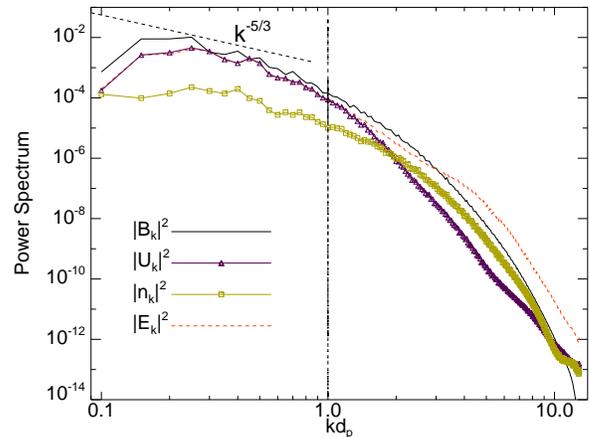


FIG. 4.— Power spectra of  $n_p$  (green-square line),  $\mathbf{u}_p$  (purple-triangle line),  $\mathbf{B}$  (black-solid line) and  $\mathbf{E}$  (red-dashed line).

different colors (black/white) of the  $A_z$  contour lines indicate different directions of rotation of the vortices. At a careful analysis of the four plots of Figure 2, a certain correlation seems to exist between the proton and the alpha-particle current densities, revealing that the local small-scale structures of the two ion species behave in a similar way. Moreover, the electron flow generates structures at smaller scales, manifesting a more intermittent and bursty character. The coherent structures visible in the four plots of Figure 2 are not static, but evolve in time interacting nonlinearly among each others. Moreover, in between the islands, the current becomes very intense and magnetic reconnection events locally occur at the  $X$  points of  $A_z$ , indicated in the contour plot of panel (a) by black crosses. The presence of these high magnetic stress regions is a signature of the intermittent nature of the magnetic field, and this affects also the patchiness of the parallel and perpendicular heating (see below).

In the top panel of Figure 3 we report the probability distribution functions (PDF) of  $j_z^{(e)}$  (red solid-cross line),  $j_z^{(p)}$  (blue dashed-square line),  $j_z^{(\alpha)}$  (green dashed-circle line), and  $j_z$  (black dashed-triangle line). This plot clearly indicates that there is a certain ordering in the maximum values of the achieved current. The main contribution to the total current seems to come from the electrons and the protons, that develop the most intense bursty events. In contrast, the alpha-particle current structures are smoother and are concentrated on larger scales, as can be noticed from Figure 2. In the same figure (bottom panel), we report the PDF of the standardized variables obtained by subtracting the average and normalizing to the respective rms value. The Gaussian fit is also plotted (light-blue dot-dashed line) as reference. The currents  $j_z$  and  $j_z^{(e)}$  are highly non-Gaussian distributed, because they are related to the increments (gradients) of the magnetic field (and electron flows are essentially frozen-in). The proton and alpha particle contributions, on the other hand, behave more like Gaussian variables, since they are related to primitive variables of turbulence such as velocities and densities, and they do not capture high order statistics.

In order to quantify the turbulence, the power spec-

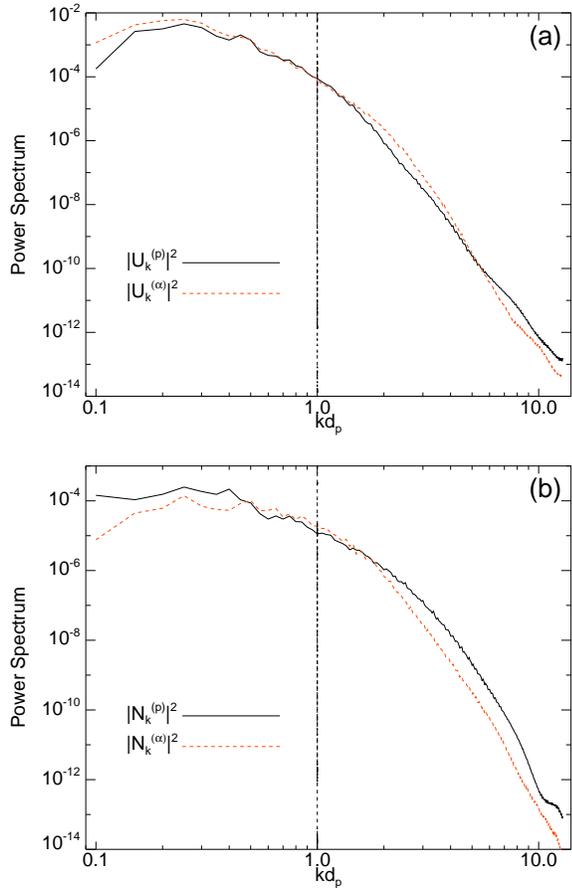


FIG. 5.— Panel (a): power spectra  $|U_k^{(i)}|^2$  of the proton bulk velocity ( $i = p$ , black-solid line) and of the alpha-particle bulk velocity ( $i = \alpha$ , red-dashed line); panel (b): power spectra  $|N_k^{(i)}|^2$  of the proton density ( $i = p$ , black-solid line) and of the alpha-particle density ( $i = \alpha$ , red-dashed line)

tra of density and bulk velocity for both protons and alpha particles and of magnetic and electric fields have been computed. In Figure 4 we show the power spectra of  $n_p$  (green-square line),  $\mathbf{u}_p$  (purple-triangle line),  $\mathbf{B}$  (black-solid line) and  $\mathbf{E}$  (red-dashed line). The Kolmogorov expectation  $k^{-5/3}$  (black-dashed line) has been plotted in Figure 4 as a reference. These omnidirectional power spectra reveal several interesting features, many of them recovered also in solar-wind spacecraft observations. In fact, the large scale activity is incompressible and the Alfvénic correlation between magnetic and velocity fluctuations is broken at the proton skin depth (vertical black dashed line). Moreover, the electric activity (red-dashed line) at higher wavenumbers is significantly more intense than the magnetic one (black-solid line) (Bruno & Carbone 2005; Bale et al. 2005). It is worth to point out that the power spectra displayed in Figure 4 present no significant differences with respect to the same spectra obtained through HVM simulations without alpha particles [see Figure 1(b) in Servidio et al. (2012)], meaning that the presence of alpha particles does not significantly affect the dynamical evolution of the turbulent cascade. To make a direct comparison of the dynamical evolution of the two ion species, in Figure 5

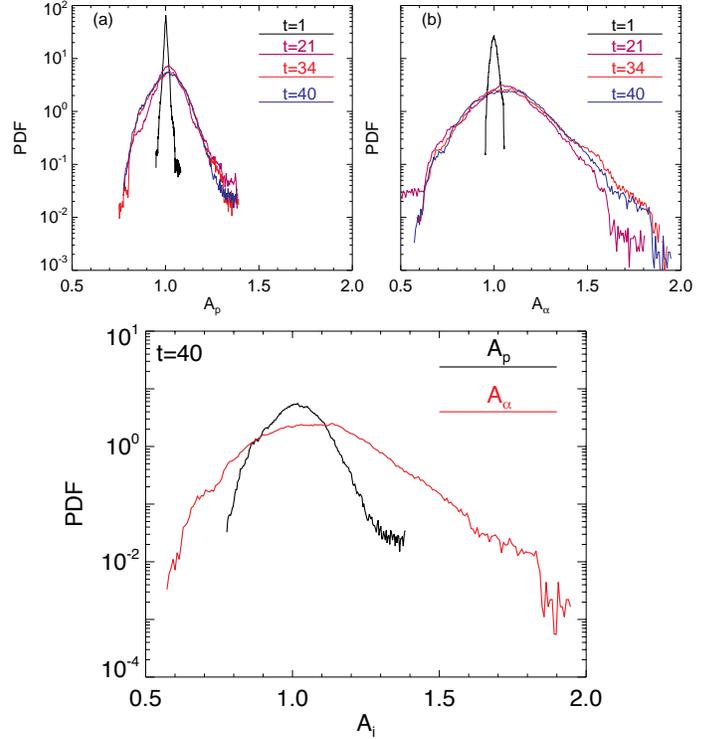


FIG. 6.— Top panel: PDF of the temperature anisotropy  $A_i = T_{\perp}^{(i)}/T_{\parallel}^{(i)}$  of protons (a) and alpha-particles (b) at four different times in the system evolution:  $t = 1$  black line,  $t = 21$  purple line,  $t = 34$  red line,  $t = 40$  blue line. Bottom panel: comparison between the proton ( $A_p$ , black line) and the alpha-particle ( $A_{\alpha}$ , red line) anisotropies is reported at the peak of the turbulent activity, i.e., at  $t = 40$ .

we show the velocity spectra  $|U_k^{(i)}|^2$  [panel (a)] and the normalized density spectra  $|N_k^{(i)}|^2$  [panel (b)] for protons ( $i = p$ , black-solid lines) and for alpha particle ( $i = \alpha$ , red-dashed lines). The density spectra for protons and alpha particles are normalized to  $n_{0,p}$  and  $n_{0,\alpha}$  respectively. While the velocity spectra [panel (a)] of the two ion species do not display significantly different features, we notice that the alpha particles contribution to the density spectra [panel (b)] is lower than the proton one for wavenumbers higher than the proton skin depth wavenumber. This behavior is possibly related to the fact that the alpha particles are heavier than protons, so their inertia does not allow to follow the field fluctuations at smaller scales.

At this point it is important to investigate the link between the turbulent behavior observed in the plasma and the generation of non-Maxwellian features in velocity space. For this purpose, the ion temperature anisotropy for each species  $A_i = T_{\perp}^{(i)}/T_{\parallel}^{(i)}$ , defined as the ratio between the perpendicular and the parallel temperature with respect to the local magnetic field, has been computed. Our initial condition has been set up in such a way to have spatially isotropic temperatures for both the ion species at  $t = 0$ . Nevertheless, during the development of turbulence the temperatures do not remain spatially isotropic but present local enhancements and depressions nearby the regions of high magnetic stress (not shown), as already found for the protons in Servidio et al. (2012).

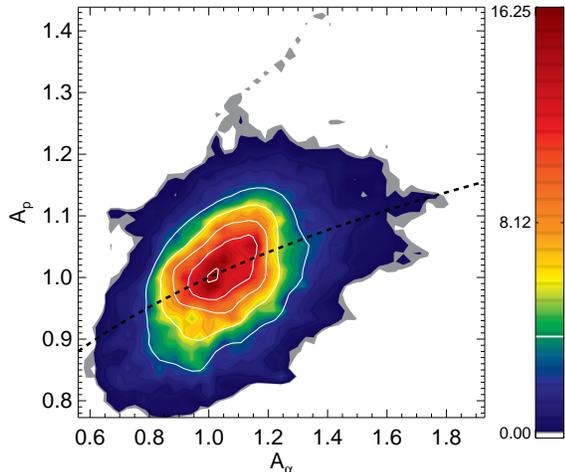


FIG. 7.— Joint probability distribution function of proton and alpha-particle temperature anisotropy. This two-dimensional PDF shows a correlation between the anisotropy in the two species. The best fit  $A_p \sim A_\alpha^\zeta$ , with  $\zeta = 0.22$ , is also reported with a thick solid line. This behavior is in good agreement with solar wind data, as it can be seen comparing this plot with Figure 1-(b) in Maruca et al. (2012).

Figure 6 shows the probability distribution function (PDF) of the temperature anisotropy for protons  $A_p$  [panel (a)] and alpha particles  $A_\alpha$  [panel (b)] at four different times in the simulation. In the early stage of the system evolution ( $t = 1$  black line), the PDFs are peaked around  $A_p = A_\alpha = 1$ , meaning that the simulation starts with an isotropic configuration. During the evolution of the system ( $t = 21$ , purple line;  $t = 34$ , red line;  $t = 40$ , blue line) the PDFs elongate in the parallel ( $A_i < 1$ ) and in the perpendicular ( $A_i > 1$ ) direction, displaying a strong anisotropic behavior. It is worth noting that the statistical behavior of the anisotropies saturates already at  $t \simeq 20\Omega_{cp}^{-1}$ . Regardless of the particular ion species, the anisotropy preferentially manifests itself along the perpendicular direction, an evidence commonly detected in the solar-wind observations (Bourouaine et al. 2010, 2011b). However, alpha particles are more anisotropic than protons, as more evidently shown in Figure 6 (bottom plot) where we have directly compared the PDFs of the two ion species ( $A_p$  black line and  $A_\alpha$  red line) when the peak of the nonlinear activity is reached ( $t = 40\Omega_{cp}^{-1}$ ).

A question now naturally occurs: are these patchy anisotropies correlated? Any correlation between  $A_\alpha$  and  $A_p$  may reveal that simultaneous kinetic instabilities locally occur, modulated by the ambient magnetic field, or that an instability for a given species may influence the other, and vice-versa. In Figure 7 we analyze the correlation between protons and alpha particle temperature anisotropy, showing the joint PDF. Although most of the events are concentrated at  $A_p = A_\alpha = 1$  (isotropy), and are broadly scattered because of turbulence, this joint distribution suggests that there is a clear monotonic dependency between alpha and proton anisotropies. The shape of this distribution is in good agreement with solar wind data, as it can be seen comparing our Figure 7 with Figure 1 of Maruca et al. (2012). Moreover, analogously to Maruca et al. (2012), we fitted the above dis-

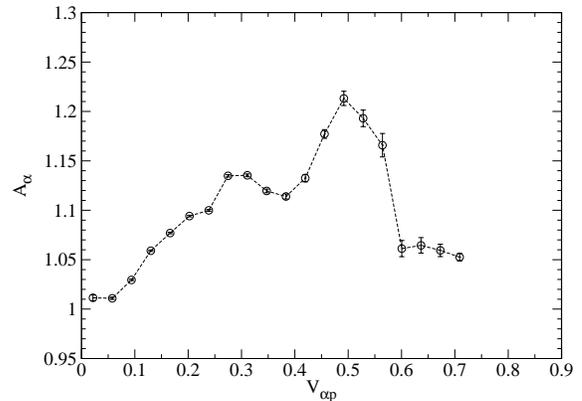


FIG. 8.— Anisotropy of the alpha-particle temperatures binned as a function of the differential speed  $V_{\alpha p} = |\mathbf{u}_p - \mathbf{u}_\alpha|$  (in Alfvénic units). This behavior is in good agreement with solar wind observations (cfr. with Figure 4 of (Bourouaine et al. 2011b)).

tribution with  $A_p = A_\alpha^\zeta$ , obtaining  $\zeta \simeq 0.22$  (note that in Maruca et al. (2012) the authors obtained  $\zeta \simeq 0.25$ ). These results suggest that the correlation between proton and alpha particle kinetic effects, commonly observed in the solar wind, may be the result of an active turbulent cascade, where kinetic instabilities are locally activated and modulated by the ambient magnetic field.

In a multi-ion plasma another source of instability is represented by the differential flow between different ion species (Gary 1993; Gary et al. 2006, 2008). We found that the temperature anisotropy for the alpha particles shows a certain correlation to their drift velocity  $V_{\alpha p} = |\mathbf{u}_p - \mathbf{u}_\alpha|$  with respect to protons. This is visible in Figure 8, where we report  $A_\alpha$  as a function of  $V_{\alpha p}$ : the temperature anisotropy increases with increasing relative flow speeds (in Alfvénic units), up to  $V_{\alpha p} \sim 0.5$ .

These results are again in good agreement with some observational analyses. Bourouaine et al. (2011b) studied correlations of temperature anisotropies and differential ion speed in the solar-wind measurements from the Helios spacecraft; for the case of the alpha particles, they found that  $A_\alpha$  increases as the ion differential speed stays below about  $0.5V_A$ . Beyond this value  $A_\alpha$  becomes roughly constant, until  $V_{\alpha p}$  exceeds a value of about  $0.7V_A$ , but then it decreases towards a value below unity when  $V_{\alpha p} \simeq V_A$  (not reached in our system). Comparing our Figure 8 with Figure 4 of Bourouaine et al. (2011b), we find a very good correspondence. However, it is worth to point out that in a different data analysis of Advanced Composition Explorer (ACE) solar wind observations, (Kasper et al. 2008) found that the alpha temperature anisotropy is monotonically decreasing with increasing alpha particle to proton relative speed in the range  $0 \leq V_{\alpha p} \lesssim 0.5$ . It is also worth noting that while these studies are carried out on years of solar wind data, that detect different plasmas with different parameters, homogeneities, large scale effects and so on, in our case, these phenomena are the genuine result of a turbulent and statistically homogeneous cascade.

To conclude our study, we discuss a few examples of the effects of turbulence on the velocity distributions of alpha particles. In Figure 9, we show the iso-surfaces of the alpha-particle velocity distribution at two distinct locations in physical space, at which  $A_\alpha > 1$  [(a)-(b)], and

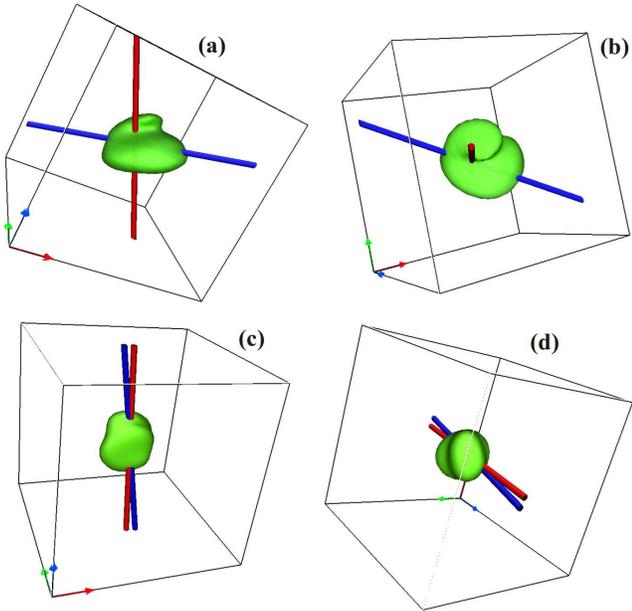


FIG. 9.— Iso-surfaces of the alpha particle velocity distribution  $f_\alpha(\mathbf{r}^*, v_x, v_y, v_z)$ , at two different spatial locations: namely in regions where the distribution function shows anisotropy  $A_\alpha > 1$  (a)-(b) and  $A_\alpha < 1$  (c)-(d). The direction of the local magnetic field (red tube) is also reported together with the principal axis (blue tube) of the velocity distribution (see Servidio et al. (2012)).

$A_\alpha < 1$  [(c)-(d)]. In the same figure, we also report the direction of the local magnetic field (red tube) and the principal axis (blue tube) of the velocity distribution, evaluated from the stress tensor in the minimum variance frame (for more details see Servidio et al. (2012)). The alpha-particle velocity distribution appears strongly affected by turbulence and modulated by the local magnetic field topology, manifesting both kinds of anisotropy; moreover, as it is clear from Figure 9, the principal axis of the velocity distribution can be both aligned or perpendicular to the local magnetic field. Another interesting feature that can be appreciated in the plots of Figure 9 is the local formation of bubbles in the velocity distribution along the direction of the local magnetic field that resemble the characteristic longitudinal beams of accelerated particles commonly observed in the solar wind data (Marsch et al. 1982a,b) and in 1D-3V HVM simulations (Valentini et al. 2008; Perrone et al. 2011). In these numerical papers a possible mechanism responsible for the generation of these beams of accelerated particles has been identified in the resonant interaction of particles with a newly identified branch of electrostatic fluctuations called ion-bulk waves (Valentini et al. 2011). This resonant interaction results more efficient for protons than for alpha particles (Perrone et al. 2011), in agreement with recent solar-wind data analysis (Marsch 2010).

#### 4. SUMMARY AND DISCUSSION

In this paper we discussed the numerical results of Hybrid Vlasov-Maxwell simulations employed to investigate the role of kinetic effects in a two-dimensional turbulent multi-ion plasma, composed of protons, alpha particles and fluid electrons, in the typical conditions of the solar-wind environment. While we pointed out that the pres-

ence of a small percentage of heavy ions does not affect the evolution of the turbulent cascade, our numerical results clearly show that the dynamics of alpha particles at short spatial scales displays several interesting aspects, mainly consisting in the departure of the distribution function from the typical Maxwellian configuration.

In a situation of decaying turbulence, coherent structures appear, such as vortices and current sheets. In between magnetic islands, reconnection events occur. We quantify the contribution to the total current due to protons, alpha particles and electrons, finding that the most of the contribution comes from the electrons, while the current density of alpha particles is very low, due to their higher inertia. Moreover, we found the currents of protons and alpha particles are Gaussian distributed, while electron current densities are highly intermittent, since they capture the small-scale features of the magnetic field.

Power spectra for protons and for the electromagnetic fields are not too much affected by the presence of alpha particles, while at smaller scales (at  $k$ 's higher than the inverse proton skin depth), the power spectrum of the alpha density has a steeper slope than that of proton density.

The non-Maxwellian features generated during the evolution of turbulence have been quantified through the statistical analysis of the temperature anisotropy in the reference frame of the local magnetic field. The joint probability distribution of the temperature anisotropies of alpha particles and protons suggests that there is a clear monotonic dependency between alpha and proton anisotropies. This reveals the occurrence of simultaneous local kinetic instabilities or the influence of the dynamical evolution of one species on the other. In general, for the parameters studied here, we found that alpha particles develop higher anisotropy than protons.

With the purpose of analyzing the role of kinetic instabilities driven by the relative speed of the two ion species, we evaluated the dependence of the temperature anisotropy of alpha particles on their drift speed  $V_{\alpha p}$  with respect to protons. From this analysis, we found that the temperature anisotropy increases with increasing relative flow speeds up to  $V_{\alpha p} \simeq 0.5$  (in units of  $V_A$ ). Moreover, the velocity distributions of alpha particles create bumps along the local magnetic field, resembling very common structures observed in the solar wind Marsch (2006).

By comparing our numerical results to recent solar-wind analyses (Maruca et al. 2012; Bourouaine et al. 2011b), we found a very good quantitative correspondence both for the correlation of alpha particle and proton temperature anisotropies and for the correlation of alpha anisotropy and relative flow speed. However, it is worth noting that, while the observational studies are carried out on years of solar wind data, that detect plasmas with very different features and in different physical regimes, in our case these correspondences are the genuine results of a turbulent cascade, where locally both the magnetic field topology and the relative motion of different ion flows can be the main sources of kinetic effects.

The results presented in this work significantly reproduce an important part of the complex phenomenology underlying many processes in the solar wind and suggest that a noise-free Eulerian Vlasov description of a

multi-component collision-free plasma plays a fundamental role in the interpretation of the observational data from spacecraft.

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