Investigation of kinetic effects in turbulence using Vlasov simulations

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Turbulence represents one of the most spectacular and unsolved problem in plasma physics, being characterized by both cross-scale couplings and kinetic effects. As the energy is injected at large scales, it is then progressively transferred to smaller scales, where kinetic effects dominate the dynamics. At these scales, complex phenomena arise, such as heating, temperature anisotropy, particle acceleration and so on. The solar wind, being turbulent and weakly collisional, is a classical example of the above scenario [1, 2, 3].

Recently, many studies have been dedicated to understand the behavior of the proton temperature anisotropy in the solar wind [4, 5, 6, 7]. In a plane described by the parallel plasma beta and the proton temperature anisotropy, indeed, *in situ* measurements reveal that solar wind measurements populate a limited area, which resembles the shape of Brazil, with the proton anisotropy being inversely proportional to the parallel beta. This general trend can be explained using adiabatic theory [5, 8], while the threshold regions may be associated with instabilities [5, 6, 7] or other processes that may operate in coherent structures [9, 10, 11]. In order to investigate the link between solar wind kinetic properties and turbulence, Vlasov kinetic simulations are needed, where the time evolution of the velocity distribution is described self-consistently in absence of particle noise.

In order to recover the characteristic shape of the *Brazil plot*, here we performed an ensemble of direct numerical simulations of the hybrid Vlasov-Maxwell (HVM) model [12, 13], in a five-dimensional phase space configuration (two dimensions in physical space and three dimensions in velocity space, 2D+3V). The Vlasov equation is solved for the proton distribution function, while electrons are considered as a fluid, using a generalized Ohm's law which retains the Hall effect. The Faraday and the Ampére equations, in which the displacement current is neglected, are included, and an isothermal equation of state for the electron pressure closes the system together with the quasi-neutrality condition. All these equations have been normalized via the

RUN	$\delta b/B_0$	β	**RUN**	$\delta b/B_0$	β
A	1/3	0.25	E	2/3	1
B	2/3	0.25	F	1/3	1.5
C	1/3	0.5	G	1/3	2
D	1/3	1	H	1/3	2.5

Table 1: Parameters of the HVM simulations, indicating the initial amount of fluctuations ($\delta b/B_0$) and the global plasma beta (β).

proton cyclotron frequency Ω_{cp}, the Alfvén speed V_A, and the proton skin depth d_p.

The initial equilibrium configuration consists of a plasma composed by kinetic ions, with Maxwellian velocity distribution and homogeneous density, embedded in a background magnetic field along the z direction ($\mathbf{B}_0$). The dynamics are in the x–y plane, with vectors that retain all three components. This configuration is perturbed by a 2D spectrum of Fourier modes, imposed for the magnetic field and proton velocity field. To avoid any artificial compressive activity, neither density perturbations nor parallel variance have been imposed at $t = 0$. Energy is injected with random phases and wavenumbers in the range $0.1 < k < 0.3$, with $k = 2\pi m/L$ (being $2 \leq m \leq 6$, and $L = 2\pi \cdot 20 d_p$ the box size). In order to mimic the variability of the solar wind, we varied the plasma beta β and the level of fluctuations, $\delta b/B_0$. The parameters for the HVM simulations are summarized in Table 1. In the two-dimensional spatial domain we use 512^2 grid-points, while the typical resolution of the three-dimensional velocity domain is 51^3 grid-points. For the simulations with smaller plasma beta ($\beta = 0.25$ and 0.5), we varied the velocity space resolution from 51^3 to 81^3 grid-points.

In analogy with fluid models of decaying turbulence, we identified the time of the peak of the nonlinear activity as the maximum of the average current density, and at this time we performed our analysis. The particle distribution function appears to be strongly affected by turbulence, exhibiting strong deformations in velocity space and resembling complex potato-like structures [14, 15]. In Fig 1 we show, for RUN G, a map of the *proper temperature anisotropy*, which has been computed in the minimum reference frame, defined as λ_1/λ_3 (λ_1 and λ_3 being the maximum and the minimum eigenvalue, respectively). See Ref. [14] for more details on this analysis. The white lines represent the in-plane magnetic field. Peaks in the proper anisotropy appear to be adjacent to reconnecting current sheets. Moreover, the study of the anisotropy direction with respect to the local magnetic field (not shown here) displays that the principal axis of the distribution function $\hat{\mathbf{e}}$ can be both along or across the local magnetic field $\hat{\mathbf{B}}$, confirm-

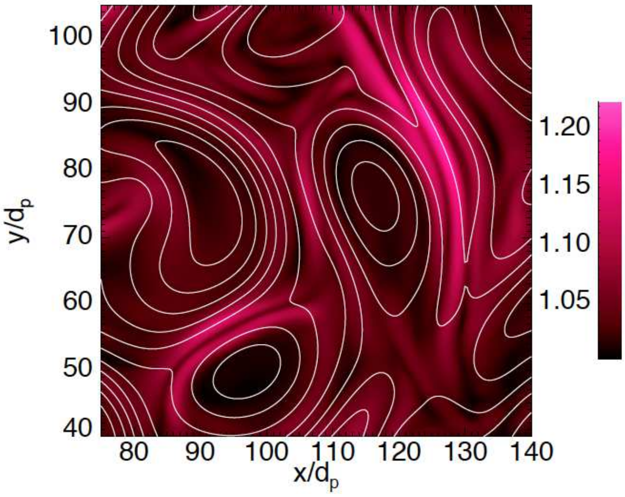

Figure 1: Zoom of the proper temperature anisotropy, defined as λ_1/λ_3, with the in-plane magnetic field lines, for the RUN G.

ing the usual definition of parallel and perpendicular temperatures. On the other hand, because of turbulence, a broad distribution of angles between $\hat{\mathbf{e}}$ and $\hat{\mathbf{B}}$ is observed, suggesting that the classical measure of temperature anisotropy underestimates the non-Maxwellian effects.

In order to reproduce the temperature anisotropy observed in the solar wind, defined now by $T_\perp/T_{||}$ (here subscripts refer to the local magnetic field), we consider an ensemble of simulations with different global parameters [16]. In this regard we varied both the level of fluctuations $\delta b/B_0$ (δb is the rms value of the fluctuations) and the global plasma β, as summarized in the Table. The left plot of Fig 2 clearly indicates that, for a fixed β (0.25 and 1 in this cases), increased level of fluctuations produces an higher level of anisotropy. As it can be seen from the right panel of Fig 2, using the entire set of simulations, the typical Brazil plot is recovered. Similar behavior has been observed with conditional analysis of solar wind data, revealing that the distribution of temperature anisotropy are strongly related to turbulence and its governing parameters.

To conclude, Partial of Variance Analysis (PVI) analysis has been performed, for the examination of magnetic, velocity and density intermittency. The analysis revealed that the strongest intermittent events are found near the threshold regions of the anisotropy plot (not shown here). These results suggest that the commonly observed temperature anisotropy is correlated with the existence of coherent structures [16]. The present results further confirm the validity of the Vlasov approach to the study of the turbulent and weakly-collisional solar wind, establishing a complex link between non-Maxwellian effects and turbulence.

Simulations were performed at the FERMI supercomputer at CINECA (Bologna, Italy) within

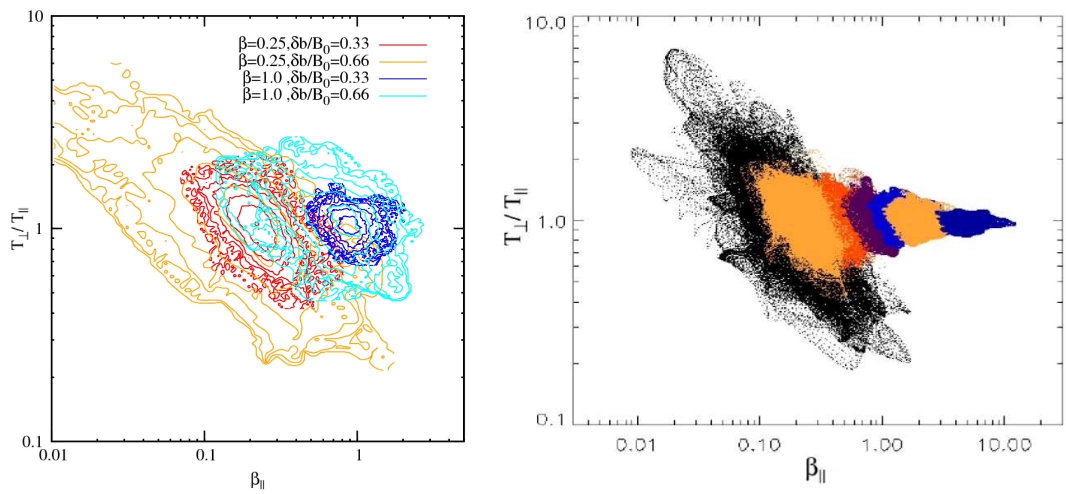

Figure 2: Left: Joint distributions of $T_\perp/T_\parallel$ versus $\beta_\parallel$, comparing different simulations. Right: Scatter plot for all the HVM simulations (see Table 1).

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