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Dynamical Evolution of Proton and Alpha Particle Distribution Functions Inside Solar-Wind Turbulence

One of the most fascinating and puzzling aspects in the dynamics the stellar medium is that the solar wind, a collisionless magnetized plasma, is hotter than expect for an expanding gas. It is thought that the reasons of this evidence is related to the turbulent character of the solar wind. The energy is transferred form large MagnetoHydrodynamics length scales to short kinetic wavelengths along turbulent cascade. The short scale phenomenology could be responsible for local heating. The solar wind mostly consists of electrons and protons, with a small amount of alpha particles and a small fraction of heavier elements. Minor and heavy ions seem to be ideal tracers of wave effects in the wind. Many spacecraft 'in situ' solar wind measurements have clearly shown that these ions are heated and accelerated preferentially as compared to protons and electrons (1-3).

We approach the study of this problem by making use of a numerical model able to describe the evolution of the turbulent cascade up to typical scales at which the system dynamics is presumably kinetic in nature. Nowadays, the increasing computational power of the modern supercomputers allows us to run kinetic Eulerian Vlasov codes (5, 7) that solve the Vlasov-Maxwell equations in multidimensional phase space. Here, we present the results of a hybrid Vlasov-Maxwell code in 1D-3V phase space configuration (one dimension in physical space and three dimensions in velocity space) that allows to study the role of minor ions in the evolution of the solar wind turbulent cascade self-consistently generated at large wavelengths by nonlinear wave-wave interactions. Within this hybrid Vlasov-Maxwell model, the Vlasov equation is integrated both for the proton and for the alpha particle distribution functions, while the electron response is taken into account through a generalized Ohm's law for the electric field, that retains Hall and electron inertia effects. The Faraday equation, an isothermal equation of state for the electron pressure and the quasi-neutrality condition close the system. We simulate a plasma embedded in a background magnetic field $\mathbf{B}_0 = B_0\mathbf{e}_x$, where x is the direction of wave propagation. Protons and alpha particles have Maxwellian velocity distributions and homogeneous density at $t = 0$. To mimic the condition of slab turbulence, in which the energy is predominantly stored in longitudinal wavevectors modes, the initial equilibrium configuration is perturbed by a set of Alfvénic fluctuations circularly polarized in the plane perpendicular to $\mathbf{B}_0$ and pro-pagating along it. The amplitude of the initial perturbation is $\varepsilon = 0.5$ and the energy is injected at wavenumbers in the range $0.078 \lesssim k \lesssim 0.23$. The initial value of the proton plasma beta is $\beta_p = 2v_{th,p}^2/v_A^2 = 0.5$ ($v_{th,p} = \sqrt{T_p/m_p}$), an appropriate choise for the case of the solar wind plasma. The phase space is discretized by using 4096 gridpoints in physical space, where periodic boundary conditions are imposed, and 51^3 in velocity space.

We numerically analyze the kinetic dynamics of protons and alpha particles when the energy is transferred along the solar wind turbulent cascade, in terms of different values of electron to proton (T_e/T_p) and alpha particle to proton (T_α/T_p) temperature ratios.

In the early stage of the system evolution ($0<t<30$), both the proton and the alpha particle distribution functions display the generation of perpendicular temperature anisotropy, but no total temperature increasing is observed for protons nor for alphas. Our simulations of decay turbulence display that the turbulent cascade, in this range of values, is not efficient in delivering enough energy to frequency of order of ion cyclotron frequency to trigger the process of cyclotron heating.

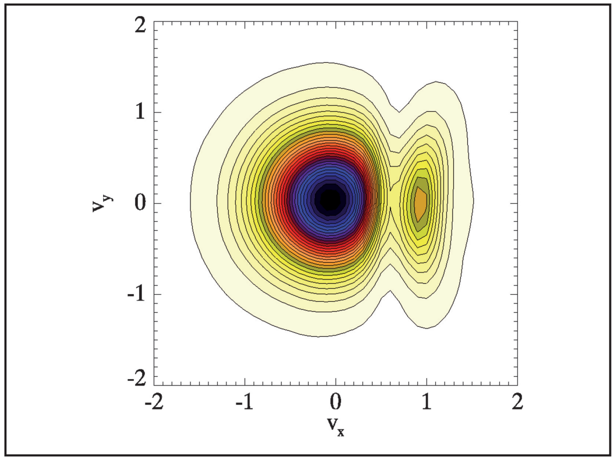

Fig. 1. – Level lines of proton distribution function in the velocity plane v_x–v_y for the case $T_e/T_p = 1$ and with $T_\alpha/T_p = 1$.

The time evolution of the electric and magnetic energies shows that, in the high wavenumbers ($k>10$) range of the energy spectrum, the level of the electric fluctuations results about five orders of magnitude higher than that of the magnetic ones and that short-scale structures are generated in the longitudinal component of the electric field. This suggests that the tail at short wavelengths of the energy spectrum is dominated by electrostatic activity. The Fourier analysis of the numerical signals shows that this short-scale electrostatic activity consists of an acoustic branch of waves (IBk waves) with phase speed $v_\phi^{(IBk)}$ comparable to the proton thermal velocity ($v_\phi^{(IBk)} \simeq 1.24 v_{th,p}$) (8, 11-13).

In correspondence of the electrostatic activity recovered at short scales in our numerical simulations, the velocity distribution of protons shows the generation of a secondary beam moving in the direction of the background magnetic field $\mathbf{B}_0$ with mean velocity close to the local Alfvén speed (Figure 1). The generation of this beam is a direct consequence of the process of trapping of protons in the potential well of the IBk waves.

By repeating our numerical experiments with different values of the initial parameters, we realized that the efficiency of particle trapping by the IBk waves for alpha particles strongly dependence the value of T_α/T_p. When the protons and alphas have same temperature, the phase speed of the IBk waves falls in the tail of the alpha particle velocity distribution. As a consequence, the alpha velocity distribution results only slightly modulated by the waves and no beam is recovered (Figure 2a).

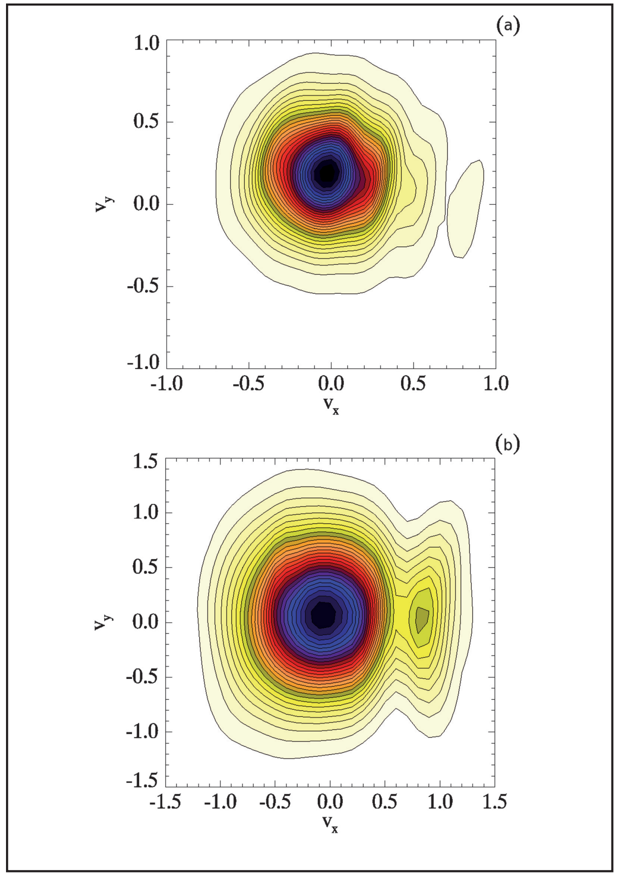

Fig. 2. – Level lines of alpha particle distribution function in the velocity plane v_x–v_y for the case $T_e/T_p = 1$ and with $T_\alpha/T_p = 1$ (a) and $T_\alpha/T_p = 4$ (b).

On the other hand, when the two species have same thermal speed ($T_\alpha/T_p = 4$) the IBk waves can efficiently trap resonant alpha particles. In this case, we observe the generation of a field-aligned beam of alpha particles with mean velocity close to Alfvén speed (Figure 2b).

The evidence that the field-aligned beam of alpha particles is observed in the simulations only for certainly values of T_α/T_p (9) could provide a possible explanation for several spacecraft observations that suggest that the generation of accelerated beams of alpha particles is a less frequent event with respect to the case of protons (6).

The electron to proton temperature ratio (T_e/T_p) does not significantly affect the results discussed so far. In our simulations we considered three different value for $T_e/T_p = 1{,}5{,}10$ (typical values of T_e/T_p for the solar-wind plasma are in the range $0.5 < T_e/T_p < 4$ (10). The physical scenario results slightly changed only for the case $T_e/T_p = 10$, unrealistic for the solar wind, for which the k-ω spectrum of the parallel electric energy displays two branches of waves with different phase speeds: the lower branch of the IBk waves with $v_\phi^{(IBk)} \sim 1.24 v_{th,p}$ and the upper branch, consisting of ion-acoustic waves with $v_\phi^{(IA)} \sim 3.6 v_{th,p}$ (in agreement with the linear theory prediction). For large values of T_e/T_p these ion-acoustic fluctuations can survive against Landau damping (4) and are visible in the k-ω spectrum, while for small T_e/T_p they are strongly dissipated.

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