1 Introduction

Understanding the physical mechanisms of turbulence represents a very old problem in fluid mechanics. In the usual picture of turbulence, in an incompressible fluid, described by Navier-Stokes equations, when the Reynolds number \( R = (V L) / \nu >> 1 \) (\( V \) and \( L \) are typical values for the fluid velocity and length scale, while \( \nu \) is the kinematic viscosity) nonlinear terms prevail, giving rise to a nonlinear energy cascade from large to small length scales. Three range of lengths \( \ell \) can be identified: an injection range \( (\ell = L) \), an inertial range where energy is transferred towards smaller and smaller lengths \( (\eta >> \ell >> L) \) and a dissipation range \( (\ell = \eta) \) where viscosity becomes the dominant physical effect. The main ingredients of this picture have been identified some centuries ago around the year 1500 by Leonardo da Vinci, nevertheless, in 1932 Sir Horace Lamb wrote: “when I die and go to Heaven, there are two matters on which I hope for enlightenment. One is quantum electrodynamics (QE) and the other is the turbulent motion of fluids. And about the former I am really optimistic”. About 60 years later Sreenivesan [1] replies: “one no longer needs to go to heaven to seek enlightenment about QE but, on Earth turbulence still defies satisfactory description”.

The situation is even more complicated when considering plasma turbulence. Apart from the macroscopic large scale range, which can be described by the MagnetoHydroDynamic (MHD) one-fluid model and then displays properties and problems similar to those characteristic of the fluid turbulence, many other smaller scale ranges characterised on the one hand by different typical lengths (ion skin depth, ion Larmor radius, electron skin depth, electron Larmor radius, etc.) and on the other hand by different physical models (two-fluid models, kinetic description, etc.) are present inside plasma turbulence.

Solar wind offers to the scientific community a unique opportunity to study plasma turbulence. In fact solar wind represents a supersonic and super-Alfvénic flow (its velocity is much larger than both the sound velocity and the Alfvén velocity \( V_A = B / \sqrt{(4 \pi \rho)} \)).
where $B$ is the magnetic field, and $\rho$ the mass density), inside which space experiments have furnished the scientific community with a wealth of data (velocity, magnetic field, plasma density, temperature etc. and also particle distribution functions) at a resolution which is not available in any earth laboratory.

Actually, due to the strong nonlinearity of the phenomena of interest, any physical interpretation of these data must heavily rely on numerical simulations. The impossibility of performing controlled experiments in astrophysics is another factor contributing to the necessity of utilising numerical simulations as proxies for real experiments. The development of numerical codes has allowed extensive and detailed numerical simulations of the dynamical evolution of plasmas in conditions as close as possible to the real ones. This usually implies the solution of the magneto-fluid equations as well as those describing collisionless or weakly collisional plasmas (*i.e.*, Vlasov and Fokker-Plank equations).

**2 MHD turbulence in the solar wind**

The solar wind is a stream of plasma mainly composed by protons and electrons (hydrogen plasma), which flows out of the Sun, due to the fact that plasma pressure associated to the very high coronal temperature (about 2 million K) overcomes the Sun gravity. The plasma which constitutes the solar wind is in a highly turbulent state. Inside such turbulence a lot of plasma physics processes occur on a very wide range of scales going from $10^{11}$ m (about 1AU) to 10 m (the electron Debye length), thus covering ten orders of magnitude. In many cases, due to different coupling mechanisms, such processes are related to one another, and all contribute to determine the complex phenomenology observed.

In the ecliptical plane, which represents the region of the interplanetary medium most widely studied by space experiments, the plasma flow is structured in high- and low-speed streams, the average wind speed increasing with heliomagnetic latitude, while the heliospherical current sheet separating the global
solar magnetic polarities is embedded within low-speed streams. At high latitudes, the wind consists of a remarkably homogeneous (at least at solar minimum) flow with wind speed in the range 750–800 km s\(^{-1}\), while the low-speed wind flows at low latitudes with a speed of 300–400 km s\(^{-1}\) and is extremely variable (see fig. 1). The high-speed wind originates from the open magnetic field lines in the coronal holes, while the low-speed streams must originate from field lines adjacent to if not within the coronal activity belt (coronal streamers and active regions).

Inside this flow, large-amplitude fluctuations, with frequencies lower than the ion-cyclotron frequency, extend over a very wide range of frequencies:

\[ 10^{-6} \text{ Hz} < f < 1 \text{ Hz}. \]

In analogy with wind tunnels, the time variations of these fluctuations, observed in the rest frame of the satellite are assumed to be due to spatial variations convected by solar-wind velocity (Taylor’s hypothesis). Assuming a solar-wind velocity \( V_{SW} = 400 \text{ km s}^{-1} \) it can be seen that the wavelengths, \( \ell = V_{SW} / f \), corresponding to (1), range from 400 km to about 1 AU.

Throughout this frequency range these fluctuations display more or less the power law spectra

\[ E(k) \propto k^{-\alpha}, \]

with observed spectral indices [2] somewhat scattered around the value \( \alpha = 5/3 \) predicted by Kolmogorov [3] for fluid turbulence (fig. 2). This fact seems to be the signature of a fully developed MHD turbulence resulting from a nonlinear energy cascade. A peculiar property of this turbulence is represented by the fact that at least in the fast homogeneous wind it is almost incompressible, in that it displays: i) a high degree of correlation between velocity and magnetic field fluctuations [4], the sign of the correlation (\( \sigma = \pm 1 \)) being that corresponding to nonlinear \( (|\delta B| / |B_0| = 1) \) Alfvén waves propagating away from the Sun); and ii) a low level (few per cent) of fluctuations in mass density and magnetic field intensity (fig. 3) [4]. Close to the heliospherical current sheet, i.e. in the slow-speed streams, large-
amplitude compressive fluctuations are found and Alfvénic correlation is destroyed.

To explain the apparent contradiction [5] between the turbulent spectrum and the presence of correlated velocity–magnetic-field fluctuations Dobrowolny et al. [6] have built a model of nonlinear cascade for incompressible and statistically homogeneous MHD, showing that turbulence evolves naturally in such a way as to enhance the velocity–magnetic-field correlation initially dominating. This conjecture has successively been confirmed by rather different mathematical techniques: numerical integration of statistical equations, obtained via closure hypothesis [7–9], simplified models for the nonlinear energy cascade [10, 11] and direct numerical simulations of MHD equations in both two dimensions [12–14] and three dimensions [15, 16].

Notwithstanding the fact that the picture of the evolution of incompressible MHD turbulence, which comes out from these theoretical models is rather nice, the solar wind turbulence, which stimulated all this work, displays more complicated behaviour. Alfvénic fluctuations propagating in opposite directions are both convected by solar wind only beyond the Alfvénic point, where the flow speed becomes greater than the Alfvén speed. One should then expect that only those Alfvén waves, which propagate away from the Sun can leave the Sun and arrive in the solar wind [4]. By supposing that the Sun is the main source of low-frequency fluctuations, the high level of correlation near the Sun and in fast streams can be understood.

In contrast, Alfvénic fluctuations, following those magnetic field lines which converge on the two sides of the heliospherical current sheet, enter the current sheet region and are subject to a dynamical evolution, during which their characteristics drastically change [17]. The main mechanisms driving the time evolution are related both to the inhomogeneity associated with the current sheet and to the opposite Alfvénic correlation of the fluctuations on the two sides of the current sheet. The results of a numerical simulation of this model by Malara et al. [17] indicate that these mechanisms could be responsible for both the lack of Alfvénic correlation and for the increased level of compressive fluctuations of slow-speed streams. Malara et al. [18] have also analysed the properties of these compressible fluctuations and compared them with those derived from space data obtaining fine agreement, in particular, concerning the occurrence of both signs of the observed n-B correlation and how this occurrence is related to: i) the fluctuations spatial scale, ii) the location with respect to the current sheet, and iii) the value of the plasma β (β represents the ratio between kinetic and magnetic pressure in a plasma).

In the following sections we will focus on a particular problem: the complex set of physical phenomena which link macroscopic (i.e. larger than the ion...
The heating of the interplanetary medium represents an exciting subject in the field of space plasma physics. A strong theoretical and experimental effort is, in fact, devoted to understanding the physical mechanisms responsible for the solar-wind gas to cool off more slowly than as in an adiabatic expansion. The local heating processes at work in the solar-wind medium are presumably triggered by the turbulent energy cascade [20]. Turbulent heating consists in a progressive energy degradation, going from large to small scales, resulting in the production, through nonlinear interactions, of fluctuations at spatial scales shorter than the ion inertial length $d_i$. Within this physical scenario, the energy injected as large-scale (Alfvénic) fluctuations is channeled towards short scales through a turbulent cascade. This nonlinear transfer can produce significant modifications of the particle distribution function (DF), which in turn may increase the collision rate and finally transform these modifications into heat. The identification of the fluctuation channels which allow the energy transfer from large to short wavelengths along the cascade represents a first crucial step to solve the problem of the solar-wind heating.

Describing numerically the solar-wind turbulent cascade from Alfvénic scales (>> $d_i$) to length scales close to the Debye length (where charge separation effects come into play) represents a gigantic challenge due to the huge separation (more than 8–9 orders of magnitude) between the involved scales. We have proposed a novel approach, which uses a combination of two different numerical models, Hybrid Vlasov-Maxwell (HVM) [21] and Vlasov-Yukawa (VY) [22], describing the dynamics of the solar-wind plasma at long (= 40 $d_i$) and short (= Debye length) scales, respectively, covering about 5–6 decades of scales. When supported by high-resolution data from space, this kind of approach could allow to shed new light on the energy transfer and heating processes in solar wind. In this perspective, we have analysed measurements in the solar wind from STEREO spacecraft and compared quantitatively space data and numerical simulation results.

The first analyses on the solar-wind data from the Helios spacecraft by Gurnett et al. [23–25] showed that in the high-frequency range (few kHz) a significant level of electrostatic activity is present in the electric power spectra. This electrostatic noise, when viewed on a time scale of several hours or more, is present a large fraction (30% – 50%) of the time [24]. This activity has been identified as of ion-acoustic (IA) nature. However, within this physical scenario, the presence of electrostatic activity in the solar wind even at small values of the electron to proton temperature ratio $T_e/T_p$ cannot be explained, since the IA waves are heavily Landau damped at low $T_e/T_p$ [26].

Recent HVM simulations analysed, at wavelengths shorter than $d_i$, the tail of the solar-wind turbulent cascade longitudinal to the ambient magnetic field $\mathbf{B}_0$ [27–29]. Within this HVM model [21] the Vlasov equation is solved for the protons, the electrons are an isothermal fluid and quasi-neutrality is assumed. These simulations showed [27–29] that the resonant interaction of protons with left-handed polarised Alfvén cyclotron fluctuations (at scales > $d_i$) generates diffusive plateaus (or small bumps) in the longitudinal velocity distribution (VD). For proton plasma beta $\beta_p = 1$, this diffusive plateau is generated in the range of velocities close to the proton thermal speed $v_{thp}$ [30]. Due to the presence of this plateau, a branch of electrostatic fluctuations (called ion-bulk (IBK) waves) can be excited through an instability process of the beam-plasma type and efficiently transfers energy from large to short scales. The IBK waves have phase speed close to $v_{thp}$, acoustic-type dispersion and, at variance with the IA waves, they can survive against Landau damping even for small $T_e/T_p$ [30]. These waves have been deeply investigated in [22–31] by means of electrostatic VY simulations, where the Vlasov equation was solved for the protons, the electrons had a standard linear Boltzmann response, but charge separation effects, ruled out from the HVM model, were retained.

4 Numerical strategy

The arguments presented in the previous section show that the results of HVM simulations and VY simulations are complementary, but a large range of intermediate scales between HVM and VY physical regimes is missing. Nevertheless, since the excitation of the IBK fluctuations is the result of a nonlocal instability process, we assumed that this intermediate range of spatial scales does not play any peculiar role. For these reasons, we have set up a simulation analysis as follows. First, we performed a HVM simulation in $(x, v_x, v_y, v_z)$ phase space configuration. The numerical phase space domain has been discretised by 2048 grid-points in the spatial domain and 81$^3$ grid-points in the velocity domain. We simulated a plasma embedded in a uniform background magnetic field $\mathbf{B}_0 = B_0 \hat{e}_z$. The unperturbed proton DF at $t=0$ was chosen to be Maxwellian in velocity with constant and homogeneous
density. To trigger the turbulent cascade [28, 29] we excited at \( t = 0 \) the first three modes (in the wave number range \( 0.15 \leq k d_p \leq 0.46 \)) in the spectrum of perpendicular velocity and magnetic perturbations \( \partial \mathbf{U}_j(x), \partial \mathbf{U}_j(x), \partial \mathbf{B}_j(x), \partial \mathbf{B}_j(x) \), with the same amplitude \( = 0.2 \) and random phases (perturbation r.m.s. amplitude \( = 0.25 \)). These perturbations are left-hand polarised in the plane perpendicular to \( \mathbf{B}_0 \) and have wave vector parallel to \( \mathbf{B}_0 \). No density disturbances have been imposed at \( t = 0 \). This initial condition tried to reproduce the presence and the dynamical evolution of the so-called slab turbulence [6, 14, 33], characterised by fluctuations with wave vectors mainly along the direction of the ambient magnetic field and propagating outward from the Sun. Periodic boundary conditions have been imposed in the spatial domain and the proton DF was set equal to zero outside the velocity interval \([-5 v_{thp}, 5 v_{thp}]\) in each direction. At \( t = 0 \), we have also set \( \beta_p = 2 v_{thp}^2 / V_c^2 = 0.5 \) and \( T_e / T_p = 1 \). Since STEREO spacecraft does not provide data on electron temperature to guide the simulations, such a low value of \( T_e / T_p \) has been chosen in order to study the most unfavourable situation, from the point of view of Landau damping, for detecting sound-like electrostatic fluctuations.

The HVM simulation was run up to the time \( \tau = 40 \Omega_{cp}^{-1} \) when the resonant interaction of protons with left-hand cyclotron waves generates a small bump in the longitudinal VE of protons at \( \nu = v_{thp} \) [28, 29] right before the occurrence of the beam-plasma instability that would produce the excitation of the IBK fluctuations. This at point, we calculated

\[
(3) \quad f_r(x, v_x, \tau) = \int \int f(x, v_x, v_y, v_z, \tau) \, dv_y \, dv_z,
\]

whose phase space contour plot is shown at the top in fig. 4. Here, the distortions due to wave-particle interaction processes are already visible, but the excitation of the IBK fluctuations has not been triggered yet. Then, we selected a thin phase space interval (delimited by vertical white lines in the figure) of spatial length \( \delta = 0.3 d_p = 2 \pi \times 10^3 \lambda_{dp} \) (\( \lambda_{dp} \) being the proton Debye length), sufficiently small to be considered as spatially homogeneous. The value of the ratio \( d_p / \lambda_{dp} \) used has been deduced from STEREO observations. The velocity profile \( f_r(x, v_x, \tau) \), obtained as the spatially average of \( f_r(x, v_x, \tau) \) over \( \delta \), was interpolated on a finer velocity grid and used as initial condition for the VY simulations. These VY simulations were designed to analyse in great detail the phase space domain \( D = [0, \delta] \times [-5 v_{thp}, 5 v_{thp}] \), which is discretised by 16384 spatial and 1001 velocity grid-points (boundary conditions in both spatial and velocity domain for these VY simulations were the same as those employed in the HVM simulation discussed previously).

The velocity profile \( f_r(x, v_x, \tau) \) is shown at the bottom in fig. 4, in which a clear and well-defined beam is visible in the vicinity of \( v_{thp} \). The goal was then to follow, with very high numerical resolution, the dynamical evolution of the phase space region of the HVM simulation where the IBK fluctuations can be excited (as discussed in [30], the excitation of IBK waves is a localised process in space). In these VY simulations, to mimic the effects of the nonlinear cascade of compressive fluctuations, we continuously imposed on the homogeneous proton density \( n_{hp} \) large wavelength perturbations on three wave numbers in the range \( 10^{-3} \leq k \lambda_{dp} \leq 3 \times 10^{-3} \); this noise was kept on and unchanged during the all simulation (mode-freezing large-scale driver), assuming its variation to be slow compared to the time scale of the fluctuations at wavelengths \( \approx \lambda_{dp} \). As in the HVM simulation, also in the VY simulations an instability process of the beam-plasma type brings energy from large towards short scales via the electrostatic IBK channel. This has been verified by analysing the \( k \omega \) spectrum of the electric signals, which has revealed the presence of a branch of fluctuations at phase speed \( = v_{thp} \) (the IBK branch); it is worth noting that no sign of IA activity has been recovered, this being due [30] to the strong Landau damping of IA waves at \( T_e / T_p = 1 \).

The synthetic electric signals obtained through the numerical simulations discussed above have then been compared to the electric waveforms acquired by STEREO spacecrafts, in the solar wind at 1 AU from the Sun, in the period March 2007-December 2009. Electric field data from STEREO are acquired at very high frequency resolution, needed for a precise comparison with the simulations. We used voltage data from the Time Domain Sampler (TDS) of the WAVES instrument onboard STEREO spacecraft, which captures and stores snapshots of electric
potential waveforms at two sampling rates (4 $\mu$s and 8 $\mu$s), having a total duration of $\sim$130 or $\sim$65 $\mu$s. The selected signals, spanning a range of frequency between 0.1 and 125 kHz, are characterised by a peak in the electric power in the range 1–5 kHz.

Performing a standard Minimum Variance analysis for the considered events, it has been verified that the electric signals are linearly polarised. The simultaneous measurements of voltage and magnetic field performed by STEREO allowed to investigate the direction of electric fluctuations with respect to the ambient magnetic field. The sampling rate of the magnetic field data measured by the IMPACT magnetometer is 0.125 s, so that about one magnetic field value is available for each electric event. About 73% events show $\theta < 30^\circ$, $\theta$ being the angle between electric field vector and average magnetic field vector, thus indicating that the electric fluctuations are mainly directed along the average magnetic field. Finally only 49 events for which $\cos \theta > 0.95$, i.e. the electric field is linearly polarised along the ambient magnetic field, have been retained for the analysis.

The measured electric waveforms, time intervals, velocities and lengths have been rescaled by the same characteristic parameters used for the VY equations, evaluated from the plasma measurements by PLASTIC onboard STEREO. Therefore, both for numerical and observational data, times were scaled by the inverse proton plasma frequency $\omega_p^{-1}$, velocities by $v_{thp}$ and lengths by $\lambda_{De} = v_{thp}/\omega_p$. The electron Debye length in scaled units is $\lambda_{De} = \sqrt{(T_e/T_p)}$ while the electric field is normalised to $E_0 = (m_p v_{thp} \omega_p)/e$.

It is also worth noting that the value of $\beta_p = 0.5$ used in the simulations is consistent with observations from STEREO, where we it has been recovered that 89.7% of the events has a proton plasma beta in the range 0.5 $\leq \beta_p \leq$ 1.

In the solar wind, the measured frequency $f_{obs}$ is Doppler shifted as

$$f_{obs} = f + (k V_{SW})/(2 \pi) \cos \theta_{kv},$$

where $f = k v_\phi/(2 \pi)$ is the real frequency of the fluctuations, $v_\phi$ their phase velocity and $\theta_{kv}$ is the angle between the wave vector and the solar-wind speed. For the analysed events $\cos \theta = 1$ thus suggesting that the direction of the wave vectors is close to the direction of the average magnetic field, i.e. $\theta_{kv} = \theta_{BV}$.

Assuming the wave phase speed of the fluctuations to be much smaller than the solar-wind velocity (Taylor hypothesis) gives an expression for the wave number as

$$k = 2 \pi f_{obs} / (V_{SW} \cos \theta_{by}).$$

This last expression allows to easily move from the time variable $t$ to the space variable $l$ through the formula $l = t V_{SW} \cos \theta_{by}$, where $\theta_{by}$ is calculated from the data.
5 Comparison between simulation results and observational data

The electric energy spectra of the observed signals display a well-defined peak in the range of frequencies of few kHz. Peak amplitude and wave number have been evaluated through a Gaussian fitting procedure, which gives rise to an estimated statistical error of 2% (amplitude) and 1% (wave number).

The observational amplitudes and wave numbers have then been compared to the results of the simulations (where analogous spectral peaks are recovered) obtained by varying the large-scale density noise level in the range $0.05 \leq \delta n_p / n_{op} \leq 0.625$. Peak amplitudes after the saturation of the instability and wave numbers, have been obtained for different values of the density disturbance. For $\delta n_p / n_{op} < 0.1$, no instability is recovered. The amplitude of the electric field increases by increasing the density fluctuation level. The minimum value from data and simulations is strictly similar being $\approx 1.5 \times 10^{-8}$ and $\approx 4 \times 10^{-8}$, respectively. The presence of an observed minimum amplitude, whose value has been reproduced by the simulations, suggests that the excitation of these short-wavelength electric fluctuations is a threshold phenomenon. Moreover, 94% of the measured peak wave numbers is in the range $0.13 - 0.24$, this observational evidence being also well reproduced by the simulations, since the simulated peak wave numbers are restricted to the same interval. The values of the peak wave number can be understood in the framework of linear Vlasov theory. By using the velocity profile $f_v(x, v_x, t)$ in a linear Vlasov solver, that numerically computes the Landau complex integral, a wave dispersion relation of the acoustic type with phase speed close to $v_{thp}$ and a region of unstable wave numbers are recovered. The value of the most unstable wave number $k^*$ increases as $T_e / T_p$ increases, being $= 0.3$ when $T_e / T_p = 1$.

From this simplified approach one can argue that STEREO events with peak wave numbers $> 0.3$ could correspond to situations in which $T_e / T_p > 1$. Unfortunately, since measurements of $T_e$ are not available from STEREO, we could not be conclusive on this point.

In fig. 5, as an example, we show an observed electric signal (top), projected on the direction along which the electric field displays the largest fluctuations (maximum variance direction), and a waveform from the VY simulation with $\delta n_p / n_{op} = 0.2$, after the saturation of the instability (bottom), as functions of the spatial coordinate (normalised to $\lambda_{dp}$), over the same spatial interval of 1000 $\lambda_{dp}$. These plots indicate that the amplitude of the electric field from the VY simulation is effectively comparable to that from STEREO and the two waveforms display the same characteristics of impulsively spiky behaviour with comparable variation scales. Finally, fig. 6 shows the electric energy spectra as a function of the wave number for STEREO events (black) and for VY simulations (red) for a density disturbance level $\delta n_p / n_{op} = 0.25$. A marked peak is visible for both
the numerical and the observational spectra in the range $0.2 \approx k \lambda_{DP} \approx 0.3$. The maximum value of observational and numerical peaks is significantly comparable and the shapes of the spectra are remarkably similar.

We emphasise that the kinetic contribution of the electrons is ruled out from our numerical model. Through simple analytical estimations of the linear kinetic contribution of the electrons in the propagation of acoustic-like fluctuations [27], one can argue that the effect of the electron Landau damping would be relevant in the high wave number range of the electric spectra in fig. 6 and could account for the difference in the concavity of the tail of the observed and simulated peaks. However, the kinetic role of the electrons on the excitation of IBK fluctuations at frequencies of few kHz deserves a deep numerical investigation and will be the subject of future analyses.

6 Summary and conclusions

The results presented indicate that electrostatic fluctuations propagating along the background magnetic field can be identified in the range of frequencies of few kHz in the solar wind. The observed phenomenology is reproduced by high-resolution Vlasov numerical experiments which allowed to investigate the physical mechanisms leading to the excitation of these electrostatic fluctuations and provided an interpretation of the space observations.

In particular, the analysis reported above provides a strong support to the identification of the electric signals from the solar-wind observations in terms of the IBK waves [29, 31].

As already mentioned, STEREO spacecraft does not provide information about the value of $T_e / T_p$; therefore, in our study we considered the situation which is the most unfavourable to excite acoustic-like waves. In these conditions, traditional IA waves cannot survive Landau damping (see ref. [30]). It is, however, possible that, for the electric events detected by STEREO, $T_e / T_p$ achieves sometimes values larger than unity which can allow for the excitation of IA waves. In this case, one cannot exclude that the electrostatic noise observed in the solar wind is composed by both IA and IBK fluctuations. However, one cannot be conclusive on this point, since the information on $T_e / T_p$ from observations is missing and, moreover, an $\omega$-$k$ spectrum cannot be deduced from the observational electric signals. Nevertheless, the main goal of this paper was to point out that the solar-wind electrostatic noise recovered even at $T_e / T_p = 1$ (which is, however, the typical and most common value for the solar-wind plasma) can be interpreted in terms of IBK fluctuations and that at such a low value of $T_e / T_p$ no sign of IA activity is recovered at high frequency (small scales) in the simulations.

It is our opinion that these results represent a milestone in the study of plasma turbulence through the understanding of the complex phenomenology occurring in space plasmas and involving scales separated by more than 4–5 orders
of magnitude. This work can be considered as a first step towards the solution of the solar-wind heating problem. Much work remains yet to be done: in particular, we have to understand if and how particle collisions convert the reversible modifications in the particle DF into heat.

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