High-resolution hybrid simulations of turbulence and kinetic instabilities in the expanding solar wind

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ABSTRACT

Turbulence in magnetized collisionless plasmas, such as the solar wind, is one of the major challenges and open questions of space physics and astrophysics. A vast store of data coming from space plasma missions indicate that kinetic interactions are active in the solar wind and that processes at small length scales are crucial for a proper understanding of the dynamics of the plasma from the solar corona outwards. Here we present results from high-resolution hybrid (fluid electrons and particle-in-cell protons) two-dimensional (2D) and three-dimensional (3D) simulations of decaying turbulence, also accounting for the effects of the solar wind expansion. This project is aimed at describing the features of the turbulent cascade in the sub-ion range, identifying dissipation mechanisms and investigating the development and interplay of turbulence and kinetic processes in the expanding solar wind. It required a large amount of High Performance Computing (HPC) resources in order to: i) employ the very high accuracy needed to model small-scales kinetic processes, ii) perform a parameter study (large number of simulations), iii) model the solar wind expansion (very long evolution), and iv) model full 3D systems.

INTRODUCTION

Model and numerical code

We use the hybrid model, which treats the ions as discrete particles and the electrons as a massless, charge-neutralizing fluid. The **hybrid expanding-box (HEB) model** let us simulate the solar wind expansion. Our simulations are performed with the **hybrid particle-in-cell code CAMELIA** (terezka.asu.cas.cz/helinger/camelia.html), which implements a pure MPI parallelization (an MPI+OpenMP version is under development), and a parallel I/O using the HDF5 library. It has been run on many different machines and it proved an optimal scalability up to at least 16384 computational cores.

Physical and numerical setting

Out initial setting consists of an ambient magnetic field in the z direction and a spectrum of large-scale Alfvénic magnetic and kinetic fluctuations in the perpendicular plane. We performed 2D simulations with 2048^2 square grids and up to 16000 particles-per-cell (ppc), i.e., more than 30 billions total particles, and 3D simulations with 512^3 cubic grids and 1000 ppc. Both settings require about 3 TB of RAM and can be run on 4096 cores in just **a few hours of walltime**. When including the effect of expansion, we have to model a much longer evolution so a few days are needed.

HPC Resources

Allocation	Type of project	Machine	Core hours
HYBTURB	CINECA Iscra-C	Fermi (Tier-0)	1.000.000
HYBREAK	CINECA Iscra-C	Galileo (Tier-1)	200.000
HYBTURB3D	CINECA Iscra-B	Fermi (Tier-0)	5.000.000
HYBTURB3Db	PRACE DECI-13	Cartesius (Tier-1)	800.000

The two Iscra-C allocations have been already exploited, while the Iscra-B and the DECI allocations are still active. We have recently been awarded 100 TB of storage at CINECA thanks to a DECI and EUDAT joint call.

RESULTS

Very high accuracy: agreement with observations

By means of accurate, state-of-the-art 2D simulations of decaying turbulence with an out-of-plane ambient magnetic field **[1,2,3]**, we could cover three decades in wavenumber and provide the first direct numerical evidence of the *simultaneous* occurrence of many features observed in the solar wind spectra **[Fig. 1]**. These include (i) a power-law scaling of the spectra of the magnetic and kinetic fluctuations and of the residual energy (their difference) in the MHD range, with different spectral indices (-5/3, -3/2 and -2, respectively), (ii) a magnetic spectrum with a clear double power-law scaling separated by a smooth break at ion scales, (iii) a strong coupling between density and magnetic fluctuations at small scales with a spectral index ~ -2.8 **[Fig. 2]**. Our results indicate that the ion-scale spectral break in the solar wind spectra results from the natural continuation of a large-scale MHD turbulent cascade through ion and down to electron scales.

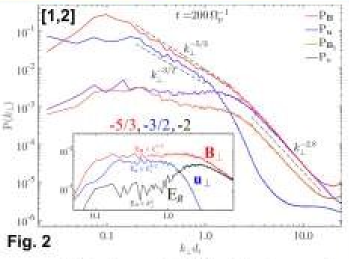

Fig. 2

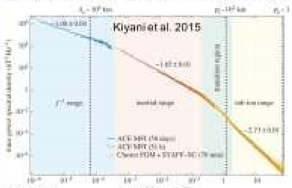

Fig. 1a

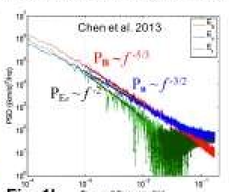

Fig. 1b

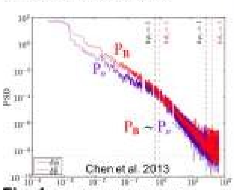

Fig. 1c

Parameter study: effects of the plasma beta β

By performing a series of twelve state-of-the-art 2D simulations with different parameters **[4]**, we investigated the effects of β (the ratio of the plasma pressure to the magnetic pressure) on kinetic turbulence. The spectral index in the kinetic range and the shape of the spectrum around ion scales vary with β **[Fig. 3]**: the transition is smoother for low β and sharper for high β. The scale of the break is related to the ion inertial length, d_i, for $\beta \ll 1$ and to the ion gyroradius, ρ_i, for $\beta \gg 1$ **[Fig. 4]**, as found in solar wind observations **[Fig. 5]**. For $\beta \sim 1$ a combination of the two ion scales better reproduce the position of the spectral break. Our numerical results suggest that the break is likely related to the presence of kinetic Alfvén waves in the high-beta regime while it could be mainly due to the dissipation occurring in reconnecting current sheets in the other limit.

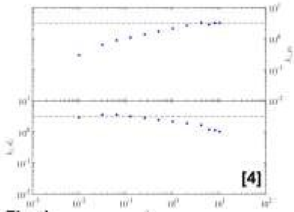

Fig. 4

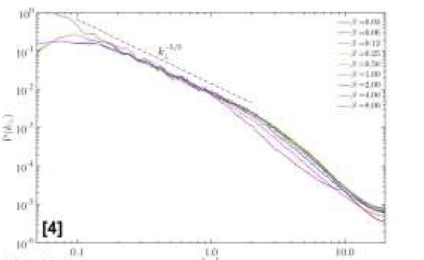

Fig. 3

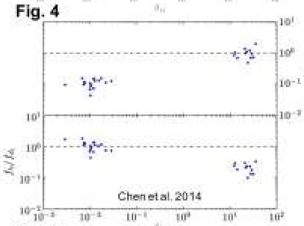

Fig. 5

Long evolution: effects of the solar wind expansion

By performing hybrid simulations employing the novel hybrid expanding-box (HEB) model, we modelled the relationship between plasma turbulence and kinetic instabilities in a slowly expanding solar wind **[5]**. The imposed expansion leads to generation of a large parallel proton temperature anisotropy, A_p, which is at later stages partly reduced by turbulence **[Fig. 6]**. The turbulent heating is not sufficient to overcome the expansion-driven anisotropic cooling, in agreement with in situ observations, and the system eventually drives the oblique firehose instability in a form of localized nonlinear wave packets which efficiently reduce the parallel temperature anisotropy **[Fig. 7]**. Our results clearly show that kinetic instabilities may coexist with strong plasma turbulence and bound the plasma parameter space.

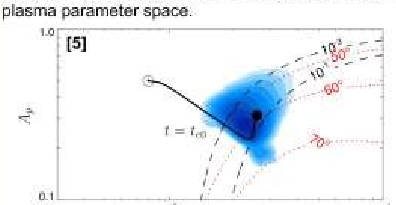

Fig. 6

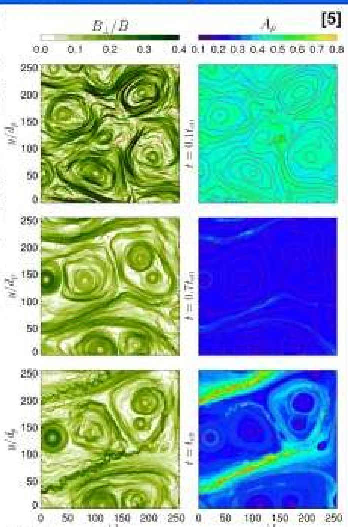

Fig. 7

3D simulations: full dynamics of turbulence and instabilities

The 2D geometry strongly constrains the dynamics: it affects the propagation of modes, inhibits the presence of small-scale parallel waves, constrains the role of possible competing mechanisms such as MHD and kinetic instabilities, and limits the shape and size of dissipative structures. We performed 3D simulations of strong decaying turbulence in presence of a guide field, starting from the simple condition of an isotropic spectrum. Up to now, we have employed at most 512^3 cells and 800 ppc, covering almost two full decades in wavenumber, but we need and plan to further increase the accuracy. We observe the development of a turbulent cascade **[Fig. 8]** with a Kolmogorov scaling and a ion-scale transition in the omnidirectional 1D spectrum of the magnetic fluctuations **[Fig. 9]**. The 2D spectrum shows a large spectral anisotropy **[Fig. 10]**, despite the initial isotropy, confirming that the cascade mainly develops in the direction perpendicular to the guide field.

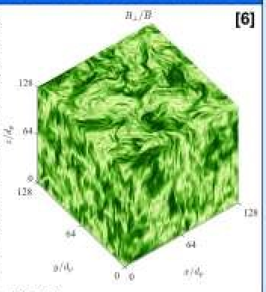

Fig. 8

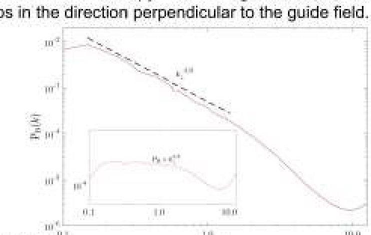

Fig. 9

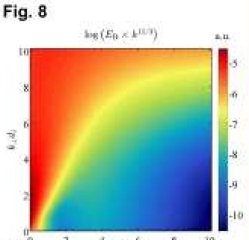

Fig. 10

FINAL REMARKS

The hybrid model is a very robust and reliable tool for covering simultaneously many decades in wavenumber, provided that a very high accuracy is exploited. State-of-the-art hybrid simulations represent a rare occasion to investigate the development of turbulence from large fluid-like scales to small sub-ion scales and its interplay with the expansion. They are fundamental to further advance in our understanding of space plasmas, to interpret data from space missions and to plan future ones (e.g., **THOR** by ESA).

FUTURE WORK

We plan to improve our 3D numerical study by modelling larger systems (1024^3 grids, ~24 TB of RAM) and by using a more realistic initial condition as driver for the turbulent cascade, i.e., a magneto-fluid instability which can trigger magnetic reconnection. A very high accuracy will be mandatory in order to cover simultaneously the large injection scales and the small kinetic scales. The proposal **"TurboRec3D"** has been submitted to the 13th PRACE Project Access Call and is currently under evaluation.

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