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Turbulence spectral anisotropy and energy flow at ion scales

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Abstract. We have analyzed the spectral properties and the anisotropy of the energy transfer rate in plasma turbulence by using high-resolution three-dimensional simulation of decaying turbulence at kinetic scales. We made use of an hybrid-PIC approach where ions are treated as particles and electrons as a massless fluid. Th simulation was produced at KNL-MARCONI, a Tier-0 system facilities of CINECA, using the INAF 2017 call (grant INA17_C3A22a). The simulations produced are state-of-the-art in terms of resolution and number of particles integrated in the system, and was used to analyse the energy transfer rate and spectral anisotropy at ion kinetic scales. A short summary of the resources allocated and the results obtained is here reported.

1. Introduction

Rarefied magnetized plasmas are ubiquitous in the astro-physical context. There, Coulomb collisions are so rare that nonlinear couplings driven by large-scale medium motions induce a turbulent cascade that reaches the kinetic scales of the plasma constituent (ions and electrons) before collisional effects start to dissipate its flux. Turbulence in such collisionless/weakly collisional plasmas is not well understood and remains one of the challenging problems of astrophysics (for a review see e.g. Alexandrova et al. 2013). The details on how electromagnetic energy is dissipated are of fundamental importance to understand heating mechanism responsible for the formation of hot stellar coronae and winds. At large scales the magnetic power fluctuations show time-series close to $f^{-5/3}$ and, because of the nature of the MHD fluctuations, the power is strongly anisotropic respect to the local mean field with the parallel spectrum deployed of energy and then steeper. Around ion characteristic scales the power spectrum modifies and the nature of its spectral anisotropy also changes. Such behaviour can be related to different physical reasons:

(1) the change in the non-linear interactions which regulate the turbulent cascade (e. g. Schekochihin et al. 2009),

(2) purely ion kinetic effects (wave-particle interactions and resonances) which transfer electromagnetic energy to the ions (e. g. Passot & Sulem 2015),
(3) and/or strongly intermittent nature of the turbulent cascade at such scales (e. g. Boldyrev & Perez 2012).

An investigation of the nature of the turbulent cascade crossing ion scales can be done via numerical simulations by using the so-called hybrid approach where the ion's Vlasov equation is solved using a particle-in-cell approach and, because of the large difference on masses, electrons are treated as a neutralizing, isotropic fluid. Our unit has successfully used such approach in simulating the turbulent transition near ion scales by performing very high resolution simulations both in 2D (Franci et al. 2015b,a, 2016) and, more recently, in 3D (Franci et al. 2018).

The resources we obtained from the Call have been employed for the production of a set of simulations related to plasma turbulence at sub-ionic scales. For this goal we made use of a numerical method which solves the Vlasov equation of ions through the PIC representation (Particle-in-cell), and treats the electrons as a neutralizing fluid without inertia (hybrid approach). The employed code, CAMELIA (`http://terezka.asu.cas.cz/helinger/`), allowed 3D simulations at very high resolutions (up to 512^3 grid points and 2048 ppc, which implies the integration of motion of 64×10^9 ions). The code is optimised with MPI and OpenMp procedure and show an excellent scalability Franci et al. (2018) The numerical and physical relevant parameters of the highest resolution simulations are reported in Table 1.

The highest resolution simulations required 16384 cores on 256 nodes, using the whole set of physical cores of each node with more than 24 GB per node (the RAM employed by the particles is around 6 TB in total for the highest resolution simulations).

The analysis of the simulations focused initially on the spectral anisotropy of the turbulence at kinetic scales. Simulations produced very high quality results, and proved that, contrary to what expected from the traditional turbulence models, spectral anisotropy at kinetic scales does not increase (Landi et al. 2019a,b). The result point out a fundamental role of the intermittence, and suggests that the non-linear interactions are strongly focused in space (and time), probably in correspondence of current sheets where resistive instabilities are at work.

The simulations have an high impact, and we expect that their data will be very useful for future projects: at the moment we are analyzing the energy transfer cascade rate (based on generalized Yaglom's law for stationary turbulence) and the intermittence properties of the turbulence at kinetic scales computing the structure function of higher orders.

The study of the spectral properties of the turbulence and of the ratio between linear and non linear time require the computation of the electr-magnetic and kinetic energy density as a function of the scale. In particular is required the knowledge of the so-called second-order structure function

$$SF_2^{(2)}(\mathbf{r};\mathbf{A}) = \left\langle (\mathbf{A}(\mathbf{x}+\mathbf{r}) - \mathbf{A}(\mathbf{x}))^{\mathbf{2}} \right\rangle$$

where the separation $\mathbf{r}$ is defined with respect to the local mean magnetic field (see Fig. 2 for the definition of the local reference frame). Such computation is very demanding in terms of numerical resources. From a specific allocation point it is required to measure differences and mean values with respect all the other grid point of the simulations, and, in order to have a statistically significant result, the same procedure it is then repeated on a large set of grid points. This means that we need a number of operation proportional to N^2, being N the number of collocation points.

The algorithm employed has been written by our research group, using an hybrid MPI/OpenMP approach, which allowed to use Marconi/KNL at the top of its capacity, showing an almost perfect scaling when MPI procedure was used for the inter-node communications and OpenMP for the intra-node computation.

At the end of the project, all the resources allocate have been used, most of them for the

Table 1. Physical and numerical parameter of the most relevant simulations produced during the project. Nx, Ny, and Nz are the grid point in each direction with size dx, dy, and dz and ppc particles per cell. β_e and β_p are the electron (proton) plasma beta. The simulations consist of decaying Alfvén-like turbulence in a uniform and magnetized plasma: in the table are reported the amplitudes and the k-vectors of the injected waves.

Nx x Ny x Nz	dx	dy	dz	ppc	β_p	β_e	k_{min}	k_{max}	Ampl.
512 x 512 x 512	0.2500	0.2500	0.2500	2000	0.5000	0.5000	0.05	0.25	0.010
512 x 512 x 512	0.2500	0.2500	0.2500	2000	0.5000	0.5000	0.05	0.25	0.010
512 x 512 x 512	0.0625	0.0625	0.2500	256	0.5000	0.5000	0.10	0.80	0.025
512 x 512 x 512	0.0625	0.0625	0.1250	512	0.5000	0.5000	0.10	0.80	0.025
512 x 512 x 512	0.0625	0.0625	0.1250	2048	0.5000	0.5000	0.30	0.80	0.025
512 x 512 x 512	0.0625	0.0625	0.0625	2048	0.5000	0.5000	0.20	0.80	0.025
512 x 512 x 512	0.0625	0.0625	0.0625	2048	4.0000	4.0000	0.20	0.80	0.025
512 x 512 x 512	0.0625	0.0625	0.0625	2048	0.1000	0.1000	0.20	0.80	0.003

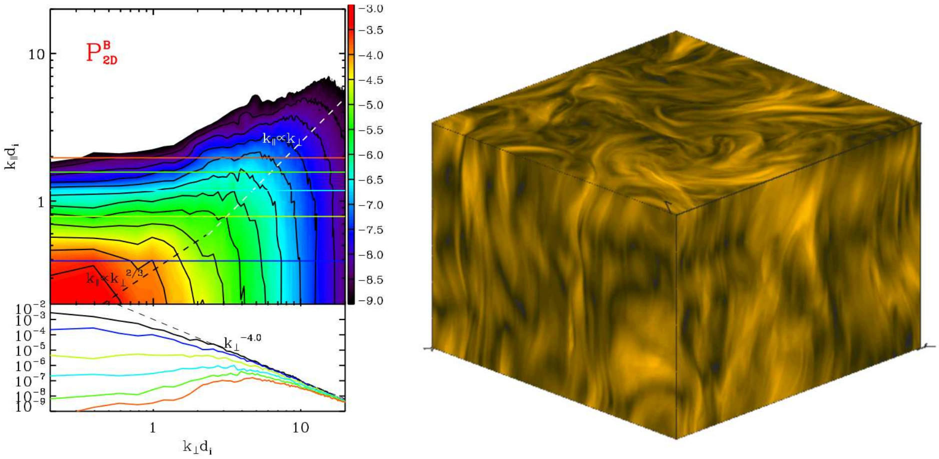

Fig. 1. Left panel: magnetic power density in the Fourier space $(k_\perp, k_\parallel)$ for a simulation of decaying Alfvénic turbulence. The energy cascade is mainly flowing in the perpendicular direction with respect the main magnetic field at large scales (small k-vectors) to then becoming of the same level at smaller scales (large k-vectors corresponding to length-scales of the order of the ion skin depth). In physical space (right panel) such anisotropy of the energy cascade at large scales corresponds to structures elongated in direction parallel to the main field (the vertical direction in the figure).

simulations in Table 1. A significant portion of core-hours was also used for the analysis of the spectral anisotropy, and a residual part for a set of hybrid 2D, MHD and Hall-MHD simulations complementary to the main simulations (which anyway produced results interesting enough to be published). The Mou INAF-CINECA has been absolutely necessary, allowing the allocation of specific and abundant resources for the computations in the astrophysical context, strongly reducing the waiting time and allowing the usage of a core-hours budget which was absolutely necessary for the success of the project.

Several articles have been published (Landi et al. 2019a; Papini et al. 2019b,a; Verdini et al. 2019; Bandyopadhyay et al. 2020; Papini et al. 2020; Franci et al. 2020b) or are now submitted (Landi et al. 2019b; Hellinger et al. 2020; Matteini et al. 2020; Franci et al. 2020a) related to this project

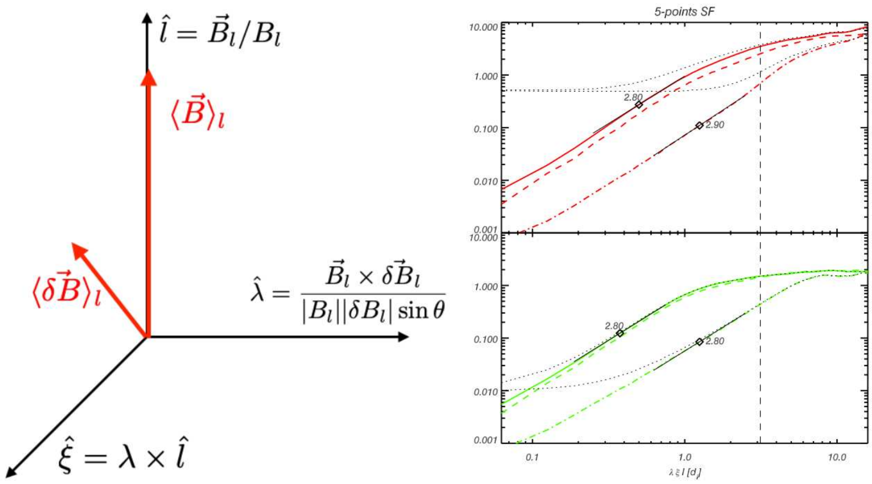

Fig. 2. Left panel: the local reference frame used to compute the second-order structure function in the simulations. Given a separation **l** from two points of the simulation, we measured the local mean field $\langle \boldsymbol{B}(\boldsymbol{l}) \rangle$ and the fluctuation with respect this mean field $\langle \delta \boldsymbol{B}(\boldsymbol{l}) \rangle$. A local frame is then built with a direction parallel to the mean field $\hat{l}$ and one axis perpendicular to the mean field and the fluctuation $\hat{\lambda}$. The behaviour of the second-order structure functions against the separation scales is reported in the right panel. Such reconstruction require a number of operation proportional to N^2, where N is the number of allocation point in the simulation.

These results have been also presented in several national and international congresses, including: Solar Wind 15, American Geophysical Union 2018 e 2019, European Geophysical Union 2018, 2019 e 2020, "Waves Cote d'Azur - A trans-disciplinary conference on nonlinearity and disorder in wave phenomena" Nice, June 2019.

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