EFFECT OF SUBGRID SCALE TURBULENCE ON PARTICLE ACCELERATION IN SOLAR WIND TURBULENCE

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Abstract In this work we analyse the role of small scale turbulent structures on the acceleration of charged particles in MHD flows in astrophysical relevant conditions. We compare the particle trajectories and statistics obtained from high resolution direct numerical simulations (DNS) and those obtained in filtered versions of these DNS fields. The filtered fields are obtained by applying a sharp Fourier cut-off on the DNS fields and represent "ideal" fields in the context of the comparison with results obtained through the large-eddy-simulation (LES) technique. All simulations are performed using a pseudo-spectral code in a cubic domain with periodic boundary conditions.

INTRODUCTION

Hydro and magnetohydrodynamic turbulence is known to play an important role in many astrophysical systems possessing high kinetic and magnetic Reynolds numbers. This is true for example in solar to stellar coronae and winds, but also in the interstellar medium (ISM), molecular clouds, accretion disks, astrophysical jet flows, etc. The turbulent dynamics influences many basic physical processes, like the heating, the acceleration and scattering of particles.

In order to gain insight about the acceleration of charged particles in turbulent magnetohydrodynamic flows, numerical simulations of turbulent plasmas provide the most extensive simultaneous diagnostic possibilities. In a Direct Numerical Simulations (DNS), one discretises the full set of MHD equations and tries to accurately capture the flow without further approximations and modelling. In turbulence research, it is well-known that with any grid based method, the memory storage cost C of a DNS to simulate a turbulent system increases with the kinetic Reynolds number as $C = Re^3$. This fact implies that, given the very high Reynolds numbers prevailing in typical astrophysical conditions, even the most modern supercomputer architectures do not have the capacity to fully resolve all scales. The main reason is of course the very nature of turbulence, in which a vast range of time and length scales are simultaneously present in the flow as a result of the turbulent cascade.

To circumvent the limitations of DNS, several approximate methods based on different modelling strategies have been devised. In particular, in a Large Eddy Simulation (LES), only the large-scale structures of the flow are simulated directly, while the small-scale structures are taken into account through a model. This way of simulating turbulent flows is supported by their phenomenology. Firstly, large-scale structures of the flow account for a very large fraction of the energy, typically over 90%. It is thus primordial to capture them accurately. Secondly, the large-scale structures are usually very sensitive to the geometry and physical setup of the problem considered. Therefore they cannot be modelled in a universal way and have to be determined on a case-by-case basis. This is in sharp contrast with the small scales of turbulent flows that are believed to be largely independent of the geometry considered because they are generated by the breaking of large flow structures through a scale cascade that erases the information pertaining to the geometry. Models representing the small scales thus have a universal character and can be developed independently of the geometry and reused in many different contexts. The main advantage of LES over DNS is that it requires only a fraction of the computer resources, and the simulation of highly turbulent flows encountered in real world applications can be considered.

In this work we explore the use of LES coupled to particle tracking in the context of astrophysical MHD flows. As explained above, in an LES, only the large-scale structures of the flow are explicitly simulated. The influence of the small scales is taken into account through a so-called subgrid scale model. Evidently, if the small scales of the flow are not explicitly present in the simulation, the particles have no way of seeing them. The natural question is then: to what extent are the particle trajectories modified because of the absence of the small-scale turbulent structures? In the context of "regular" hydrodynamic turbulence, this question has been the subject of a fairly large number of studies in the field of particle-laden flows (e.g. [5, 3]) . The particles then form a dispersive phase that is transported by the velocity field along the flow lines. In MHD cases, we are facing a completely different transport mechanism, as the particles are not advected by the flow field but are accelerated by electromagnetic fields. The equations to be solved are:

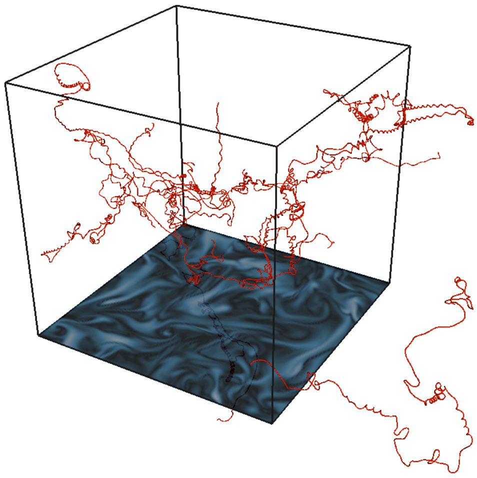
$$\partial_t \mathbf{u} + (\mathbf{u}\cdot\nabla)\mathbf{u} = -\nabla p + (\mathbf{b}\cdot\nabla)\mathbf{b} + \frac{1}{Re}\nabla^2\mathbf{u}, \quad (1)$$

$$\partial_t \mathbf{b} + (\mathbf{u}\cdot\nabla)\mathbf{b} = (\mathbf{b}\cdot\nabla)\mathbf{u} + \frac{1}{Re_m}\nabla^2\mathbf{b}, \quad (2)$$

$$\frac{d\mathbf{v}}{dt} = \beta(\mathbf{e} + \mathbf{v}\times\mathbf{b}). \quad (3)$$

In the above expressions, $\mathbf{u}$, $\mathbf{b}$, $\mathbf{e}$ and $\mathbf{v}$ are respectively the fluid velocity, the magnetic field, the electric field and the particle's velocity. β represents the strength of the coupling ($\sim q/m$) while Re and Re_m are the kinetic and magnetic Reynolds numbers. The electric field is computed from the velocity and magnetic fields using Ohm's law. All the computations are done using a pseudo-spectral 3D code in a cubic domain with periodic boundary conditions [2].

In order to study the influence of small scale turbulent structures, several high-resolution DNS databases have been generated for MHD flows in different turbulent regimes (e.g. with varying intensity of mean magnetic fields etc.) and test particles have been tracked in these 'frozen' fields (this approach is fully justified as long as the timescale for the evolution of the particles is much shorter than the MHD time scale called the Alfvén time) [1]. The corresponding particle trajectories constitute the accurate benchmarks for our LES simulations. In figure 1 (left), we plot such chaotic particle trajectories in a DNS field and in figure 1 (right) we plot the averaged mean square displacement (MSD) for a sample 5×10^5 particles in different parameter configurations [4]. In order to assess the influence of the small scale turbulent structures, the frozen MHD fields are then filtered to progressively eliminate them. This is easily done for spectral data by using a sharp Fourier cut-off with decreasing cut-off wavenumbers. The particle trajectories are then analysed in these various filtered fields and compared to those obtained in the original high-resolution fields. The analysis of the trajectories in the LES fields is still under progress and will be completed in the coming couple of months. The diagnostics that will be presented at the conference will focus on the mean square displacements of the particles and their asymptotic velocity behaviour as a function of the cut-off filter width. This work will unambiguously indicate what is the role of small-scale turbulent structures for the simulations performed.



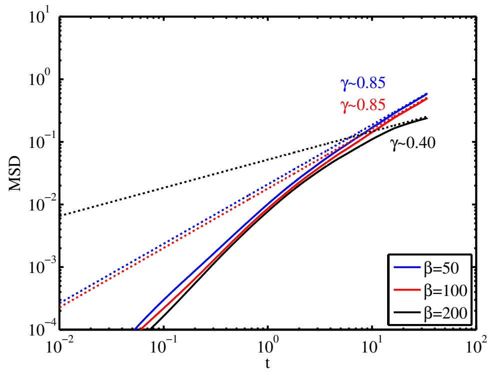


Figure 1. Left: sample charged particle trajectories in an MHD field obtained from Direct Numerical Simulation (resolution: 512^3 modes, $Re_\lambda \approx 250$). The bottom cut represents the local intensity of the magnetic field. Right: average square mean displacement of a sample of 5×10^5 particles for different values of the cpupling parameter β (the symbol γ represents the slope of the curves for large times) [4].

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