FLUID AND KINETIC MODELLING OF THE MAGNETIZED KELVIN-HELMHOLTZ INSTABILITY

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Abstract   The nonlinear evolution of collisionless plasma flows is a multi-scale process where the energy is injected at large, fluid scales and dissipated at small, kinetic scales. Accurately modelling the global evolution of collisionless plasmas requires to take into account the main micro-scale physical processes of interest, in particular the kinetic effects. We concentrate here on the nonlinear evolution of the magnetized Kelvin-Helmholtz instability in collisionless plasmas.

First, we will summarize recent works concerning fluid and kinetic modelling of the magnetized Kelvin-Helmholtz instability. Comparisons of different plasma models is today an imperative task aiming at understanding cross-scale processes in collisionless plasma turbulence. We then report new results of two dimensional fully kinetic (both electrons and ions are treated kinetically) simulations of the magnetized Kelvin-Helmholtz instability. We make use of the implicit Particle-In-Cell (PIC) code iPIC3D in 2D-3V configuration. In this work, we focus on the analysis of the effects of kinetic physics and compare results obtained with the full kinetic model to those obtained in the context of MHD and hybrid simulations. We discuss the space physics implications of the nonlinear saturation of the Kelvin-Helmholtz instability, in the context of the interactions between the solar wind and the Earth magnetosphere.

In typical laboratory, space and astrophysical conditions, plasmas are collisionless: the mean free path is often much larger than the typical lengths scales of the plasmas. Collisionless plasmas flows are thus out of local thermodynamic equilibrium. Their nonlinear dynamics is driven by the energy injected at large, fluid scales, which self-consistently cascades towards smaller and smaller scales, until kinetic effects (but no collision) come into play.

From a theoretical/modeling point of view, space plasmas represent a laboratory of excellence to study the physics of fundamental cross-scale collisionless plasma processes, because of the wealth of in-situ diagnostics. The solar wind and magnetosheath plasma turbulent state, routinely observed by satellites, is an archetype of multi-scale collisionless plasma turbulence.

Many plasmas processes naturally lead to a multi-scale dynamics, as for example at the interface between two different plasma regions, where large scale, fluid instabilities develop self-consistently and act as a source energy. This is the case of the solar wind-magnetosphere interface, which plays a key role in the context of space weather modeling and forecasting. At the transition region between the solar wind flowing plasma and the Magnetosphere plasma at rest at low latitude, nearby the equatorial plane, a velocity shear between the two plasmas is an efficient source for the development of the Kelvin-Helmholtz instability. Satellite measurements have supplied clear evidence of rolled-up vortices at the flank of the Magnetopause where the Kelvin-Helmholtz instability is thought to account for the increase of the plasma transport, in particular the solar wind plasma entry in the Earth's magnetosphere.

In its nonlinear phase, the Kelvin-Helmholtz rolled-up vortices drive the formation of gradients at small scales (the ion inertial length and/or the ion Larmor radius up to electronic scales) source of secondary hydrodynamics or plasma instabilities.

First, the density jump between the plasmas drives fluid-like secondary instabilities such as secondary Rayleigh-Taylor and the differential rotation inside the vortices is a source for secondary Kelvin-Helmholtz instability. Second, the nonlinear evolution of Kelvin-Helmholtz vortices enables the occurrence of vortex induced reconnection by large-scale vortex motions. The vortex formation process indeed drags the "frozen-in" magnetic field component parallel to the flow direction into the vortex. As a result, the magnetic field is more and more stretched inside the vortices until it reconnects, redistributing the initial kinetic energy into accelerated particles and heating, and modifying the magnetic topology inside the vortex.

It is thus crucial to establish the role of these different secondary, small-scale instabilities on the dynamics of the system, since they strongly influence the nonlinear saturation of the instability, from the hydrodynamic inverse cascade to the formation of a mixing layer (Fig. 1).

In this context, comparisons of different plasma models, from magnetohydrodynamics to kinetic models, is today an imperative task aiming at understanding cross-scale processes in collisionless plasma turbulence. After summarizing
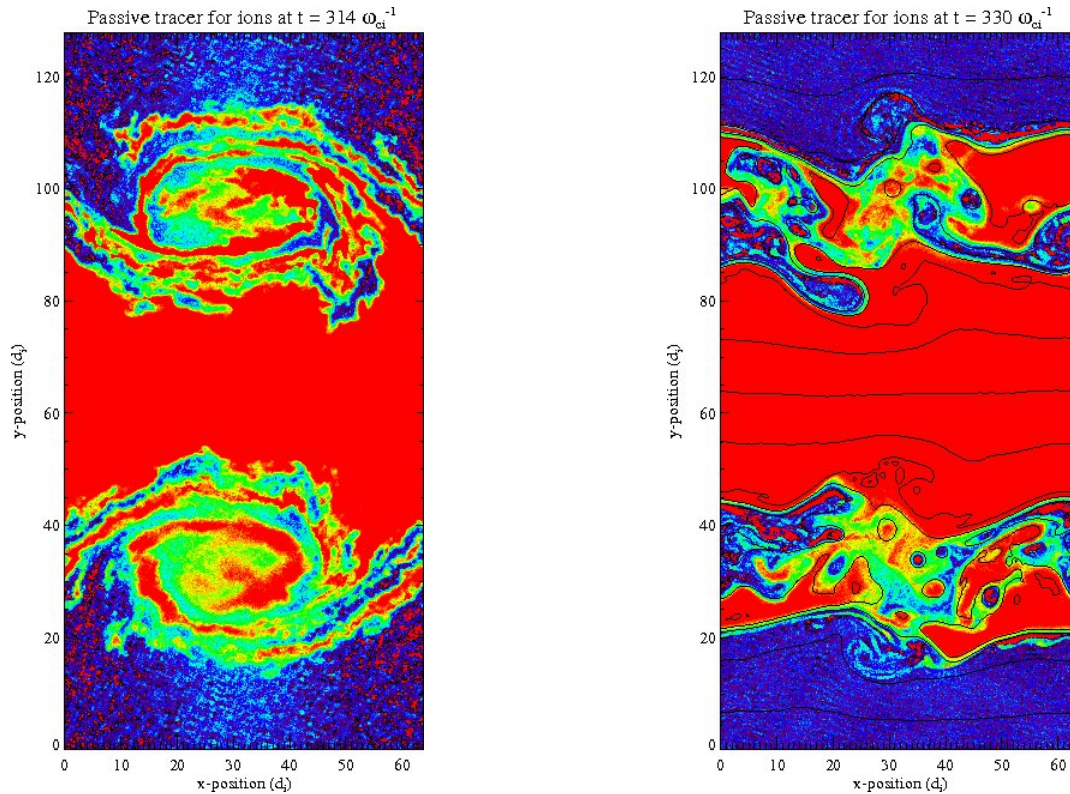
Figure 1. Nonlinear evolution of the Kelvin-Helmholtz instability in a magnetized, collisionless plasma, starting from a double shear layer, by means of a full kinetic Particle-In-Cell code. The colors show the ion density of the plasma initially on one side of the shear layers. Position are expressed in ion inertial lengths. *Left panel:* final vortex after pairing with an out-of-plane initial magnetic field. *Right panel:* vortex disruption and formation of a mixing layer due to vortex-induced reconnection when a (small) initial in-plane magnetic field is added.

recent works concerning fluid and kinetic modelling of the magnetized Kelvin-Helmholtz instability [1, 2], we will report massively multi-parallel two dimensional fully kinetic (both electrons and ions are treated kinetically) simulations of the magnetized Kelvin-Helmholtz instability (Fig. 1). We make use of the implicit Particle-In-Cell (PIC) code iPIC3D[3] in 2D-3V configuration. This model enables to explore the kinetic (non-thermal) behavior of both electrons and ions during the development of the magnetized Kelvin-Helmholtz instability in plasmas out of local thermodynamic equilibrium. In this work, we focus on the effects of small-scale, kinetic physics and compare the results obtained by means of the full kinetic model to those obtained in the context of magnetohydrodynamics and hybrid simulations.

Acknowledgments

References

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