IL NUOVO CIMENTO Vol. 32 C, N. 2 Marzo-Aprile 2009
DOI 10.1393/ncc/i2009-10364-1

Colloquia: CSFI 2008

Three-dimensional magnetic reconnection simulations using the Eulerian Conservative High Order (ECHO) code

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(ricevuto il 15 Maggio 2009; pubblicato online il 3 Agosto 2009)

Summary. — Magnetic reconnection and shear driven instabilities are pervasive phenomena in the heliosphere and in astrophysical plasmas in general. Magnetic reconnection and Kelvin-Helmholtz-like instabilities require the use of high-order numerical approximations to study their linear and non-linear evolution. At the same time, in compressible MHD the dynamical activity following reconnection processes leads to formation of discontinuous modes which should be treated by shock-capturing numerical schemes. For this purpose we have designed an Eulerian Conservative High Order (ECHO) code in which, i) explicit diffusivity is taken into account, ii) high-order numerical approximations of flux derivatives are included and iii) shock-capturing algorithms are employed in managing flux discontinuities. This code has been applied successfully in studying the linear and non-linear 3D evolution of the tearing instability and in following the 3D evolution of a current sheet embedded in a sheared flow.

PACS `95.30.Qd` – Magnetohydrodynamics and plasmas.
PACS `52.35.Vd` – Magnetic reconnection.
PACS `52.35.Py` – Macroinstabilities (hydromagnetic, *e.g.*, kink, fire-hose, mirror, ballooning, tearing, trapped-particle, flute, Rayleigh-Taylor, etc.).

1. – Introduction

Magnetic reconnection plays a fundamental role in several astrophysical environments. In the Heliosphere, several processes like coronal heating, explosive phenomena, solar-wind acceleration, properties of turbulence and particle transport are affected by the presence of magnetic-field reconnection. Fast, inhomogeneous plasma flows are also ubiquitous throughout the heliosphere such as spicules and macrospicules observed in the chromosphere and transition region, coronal plumes [1], pressure-balanced structures in the solar wind [2]. Also the bimodal structure of the solar wind at solar minimum, consisting of high-speed streams originating from the polar coronal hole, and a much slower stream surrounding the streamer belt above the solar magnetic equator [3], is an example of a differential shear flow which can exceed both the Alfvén and sound speed by factors of 5–10. All these flows are strongly coupled with inhomogeneous magnetic

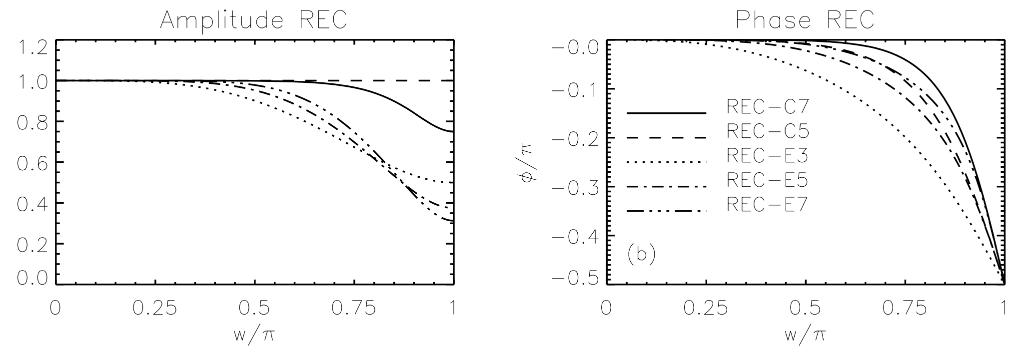

Fig. 1. – Comparison of spectral properties of different high-order explicit and implicit reconstruction procedures. The ideal reconstruction procedure should have unitary amplitude (left panel) and zero phase delay (right) for all values of the normalized wave vector w/π. In the panels are reported the spectral properties for explicit 3rd, 5th and 7th order (E3, E5, and E7) compared to compact 5th and 7th order (C5 and C7).

fields and the coupling between magnetic reconnection-driven and flow instabilities can lead to much of the phenomena observed in the solar atmosphere and wind.

In treating the heliospheric plasma we are often faced with slow-to-moderate values of the plasma beta, the ratio between the plasma to the magnetic field pressure, so that flows arising from the reconnection process are supersonic [4, 5]. Shear flows can exceed the local Alfvén and sound speed velocities and compressible fluctuations arising from Kelvin-Helmholtz instabilities can easily steepen into shock. The suitable numerical techniques for modeling such dynamics are shock-capturing, such as upwind methods with ENO (Essentially Non Oscillatory) interpolation polynomials. At the same time, resistive instabilities and magnetic reconnection require high-order spectral techniques where the diffusion coefficients may be controlled explicitly. The choice most often made to allow numerical diffusivity to explicitly dominate the resistive dynamic, does not permit to appreciate destabilizing effects driven by resistive processes. Moreover, the use of second-order numerical techniques prevents from following the fine structuring of the system caused by the non-linear evolution of flow and restive instabilities.

2. – The ECHO scheme for resistive MHD

The study of the dynamical activity caused by destabilization of a current sheet by magnetic diffusive processes in a compressible plasma has been performed using the Eulerian Conservative High Order (ECHO) code which reconciles shock-capturing properties with high-order spectral-like differentiation schemes. The code can integrate the ideal and resistive [6] set of MHD equations as well as special and relativistic equations [7, 8] in conservative form. It is based on the Upwind Constrained Transport (UCT) methodology [9, 10] for treating the solenoidal condition for the magnetic-field evolution. It is able to handle different reconstruction, derivation and interpolation procedures such as high-order explicit and implicit [11] algorithms with a proper limiter [12] as well as WENO [13], TVD and CENO3 algorithms [14] at various orders. In general there results a better spectral resolution using implicit (or compact) schemes with respect to the same order explicit procedures (see fig. 1). It allows the use of either LFF or HLL [15] Riemann solvers and time integration is performed by 3rd- or 4th-order Runge-Kutta

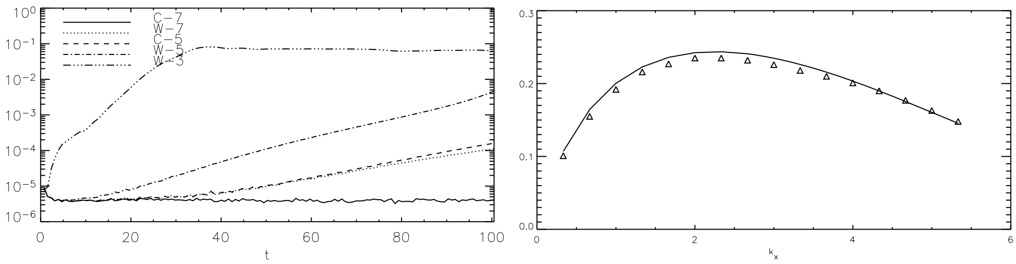

Fig. 2. – Left: measured numerical diffusivity for simulation of the tearing instability using different numerical schemes: WENO 3th, 5th, and 7th order (W-3, W-5, and W-7), compact 5th and 7th order. The experiment has been performed letting the system evolve without any explicit resistivity. Right: comparison of the measured (triangles) with predicted (solid line) dispersion relations for the tearing instability using the 7th-order compact scheme.

time stepping. ECHO is able to preserve the local divergence-free condition for the magnetic field to within machine accuracy, to satisfy global conservation laws, to well resolve small-scale structures as well as to fully appreciate explicit resistivity against numerical diffusivity (see fig. 2). Details on how the magnetic diffusivity has been handled and on the spectral-like properties of the designed numerical scheme can be found in [6].

3. – Applications

The resistive version of ECHO has been used in the study of the three-dimensional dynamic of current-sheet and current-vortex sheet with particular emphasis on the role of secondary instabilities in the transition to turbulence of an initially laminar state. Initial primary instabilities, such as tearing [16] or Kelvin-Helmholtz [17] modes, lead an

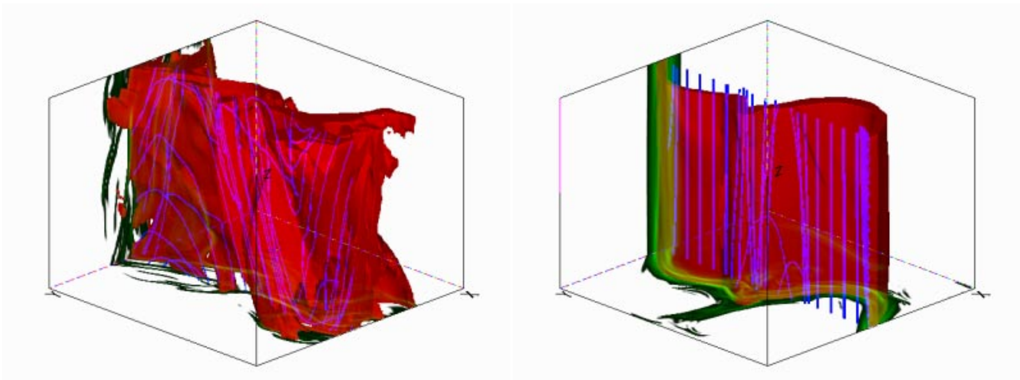

Fig. 3. – (Colour on-line) Plasma and magnetic-field representations obtained from two simulations of the tearing and Kelvin-Helmholtz instabilities in a initial configuration where a current sheet is embedded in a supersonic sheared flow. The plasma pressure isosurfaces (red), magnetic-field lines (blue) and current density intensity (green) are reported. In the left panel, a coalesced structure formed by the tearing instability is bending out of shape because of the onset of a kink-like mode. Depending on the initial geometry of the magnetic field with respect to the flow, a Kelvin-Helmholtz instability can dominate the non-linear regime (right panel).

equilibrium configuration containing current-sheet and/or flow inhomogeneities towards two-dimensional configurations that, in the saturated non-linear regime, are themselves unstable against three-dimensional ideal secondary modes, which push the system towards a turbulent state (see fig. 3). The study has been performed for the tearing instability considering different initial equilibria and different strengths of the magnetic pressure with respect the plasma pressure [6]. An analogous study for a configuration with a current sheet embedded in a velocity shear, a model of the heliospheric current sheet embedded in the bimodal solar-wind flow [18], has been also performed, taking into account different geometries of the magnetic field with respect the plasma flow [19].

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