

# Influence of environmental parameters on the Kelvin-Helmholtz instability at the magnetopause

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The Kelvin-Helmholtz instability (KHI) being the cause of the boundary layer at the interface between the Solar Wind (SW) and the Magnetosphere (MS) during Northward oriented IMF (interplanetary magnetic field) is in good agreement with the observations so far [1]. Previous works investigated the topic but most were considering simplified configurations [2, 3, 4]. The full extent of the SW/MS interaction can only be represented in a three-dimensional (3D) magnetohydrodynamic setting, accounting for the Hall term where local perturbations can act at a distance through the magnetic connectivity of the near-Earth plasma [5, 6]. In particular the double mid-latitude reconnection (DMLR) process exposed by Faganell et al. [9], triggered by equatorial KHI roll-ups, is a consequence of the differential advection of the magnetic field lines depending on the latitude which gradually induces twisting, leading to the creation of stressed field lines regions at symmetrical positions on each side of the equatorial plane. Magnetic reconnection then happens inside these regions, exchanging field lines from the MS and the SW with each other, continuously provoking the entry of SW matter into the MS.

Their previous work is extended here with a larger simulation box which allows to observe vortices interactions, the addition of a density contrast and variations in the interface profile to bring the simulation closer to actual SW/MS events. 3D simulations of KHIs at the flank of the MS during northward oriented SW are performed, where different parameters are varied to assess their influence on the growth rate of the KHI and consequent phenomena. These different configurations may have discernible signatures that can be identified by spacecraft diagnostics. The simulations presented in this article were performed using the parallelized (MPI) Adaptive Mesh Refinement (AMR) Versatile Advection Code [7] simulation tool-kit<sup>1</sup>. The plasma at the SW/MS interface is described by the resistive Hall-MHD set of equations. The introduction of the Hall term aims to take into account that the ions can demagnetize at the ion inertial length  $\delta_i = c/\omega_{pi} \approx 100$  km and break the 'frozen-in' condition usually encountered in this region, leading to an additional current term, while the magnetic resistivity will account for reconnection processes. Our system is normalized using the ion mass  $m_i$ , the ion inertial length  $\delta_i$  and the ion cyclotron frequency  $\Omega_{ci} = 0.3$  Hz.

<sup>1</sup>tool-kit and manual available in open source at <http://gitlab.com/mpi-amrvac/amrvac>

This results in an Alfvén velocity of  $\sim 150$  km/s for a magnetic field  $B=20$  nT. The initial condition uses a simplified Grad-Shafranov [9] equation and the velocity, magnetic fields and density are then derived from that vector potential. The box size is chosen larger than in [9], enough for two pairs of KH vortices to appear since in real situation there would be many vortices interacting and this is as important as the existence of a single one. The usual resolution is  $N^3=200^3$  and the boundary conditions are periodic in the  $y$ - and  $z$ -directions, while they are extrapolated continuously in the  $x$ -direction. The other parameters are the Alfvén Mach number  $M_A=1$ , the sonic Mach number  $M_c=1$ , the plasma beta parameter  $\beta=0.7$ , the half-width of the shear layer  $L_u=3$ , the magnetic resistivity  $\eta=1e^{-3}$  and the heat capacity ratio  $\gamma=\frac{5}{3}$ .

Fig. 1 presents snapshots of the time evolution showing the most important feature of our simulation at  $t_A = 600$ , where some magnetic field lines originating from the SW side (red highest density) contain MS matter (blue lowest density) around the equatorial plane (bottom slice). This is the result of the DMLR, where some field lines will reconnect on a site halfway between the equatorial plane and the edge of the box, connecting SW field lines to MS ones. The relief of this stress is quickly followed by its mirror process on the other side of the middle plane, actively turning a rope of SW into a part of the MS, releasing energetic particles in the process. This phenomenon happens on different sites and keeps on happening as long as the KHI will braid field lines together ( $t_A=700$ ). It is important to mention that this configuration can depend heavily on the physical parameters, as shown in Nykyri et al [3]. In this spirit the value of the initial physical quantities are varied to assert their influence on the growth rate and topological development of the KHI. These different variations and their effects are summed up in Fig. 2 showing the evolution of the volume averaged current  $\langle \hat{J} \rangle$  against physical time. The twisting and compressing of the field lines leads to the emergence of current sheets of variable widths and intensities.

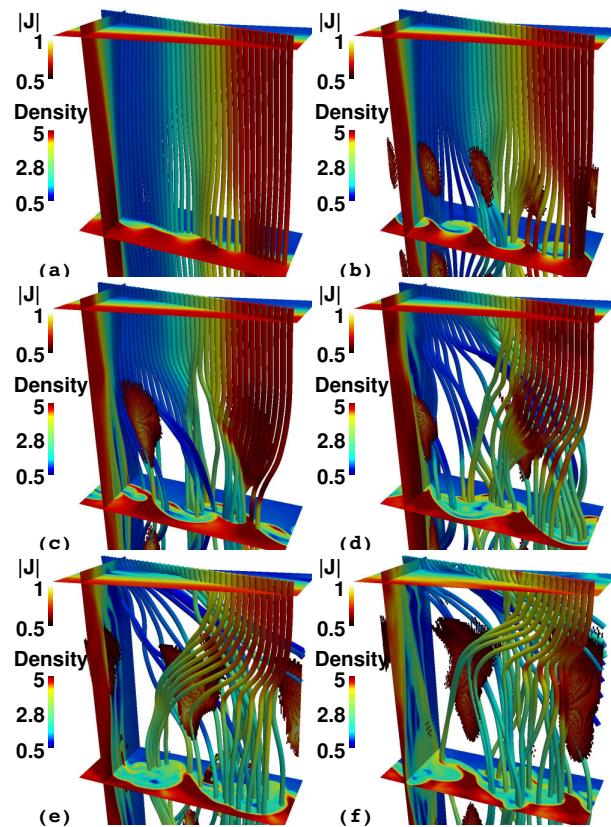


Figure 1: *Time evolution of our simulation, slices and field lines coloured with density and current magnitude above 0.5 NU in orange.*

Varying the initial density jump from  $\Delta n = 4.7$  to  $\Delta n = 7$  does not affect the growth rate of the instability but it increases the maximum value of  $\langle \hat{J} \rangle$  by around 20%. This is caused by both wider current sheets and higher maximum value of the current. While the main evolution of the KHI is not significantly disturbed by the increased density gradient, the profile of the boundary layer is affected by secondary Rayleigh-Taylor instabilities due to the centrifugal force in the vortices. On the side of the shear layer  $L_u$ , we see that the KHI develops twice faster for  $L_u=1$  than for  $L_u=3$  and the obvious conclusion is that the averaged current  $\langle \hat{J} \rangle$  reaches again a much larger value. The study on the resolution demonstrates that a larger resolution brings much wider and more intense current sheets (up to 3 times for  $N^3 = 600^3$ ), probably because the magnetic field gradient is much better resolved.

The aim of our work is also to simulate spacecraft data relevant to the KHI in these various configuration. As shown in [8], the temporal profiles of the density and magnetic field components approximate well the data coming from consecutive crossings of the magnetopause by Cluster. The rolling-up structure can be found in the almost periodic alternation between SW and MS values of the density and Alfvén velocity. In addition to synthetic spacecrafsts, the MPI-AMRVAC code offers the possibility to simulate the trajectories of particles in MHD simulation snapshots. A thermal population of particles are started at the latitude of the current sheets and the resulting spectrum and trajectories are used to try and identify behaviours specific to the DMLR. Fig. 3 displays 4 trajectories the particles can follow : bouncing outside the currents sheets (a), bouncing between the sheets (b) and bouncing inside the sheets limits (c). The trajectory (d) is a slow particle that has not joined a population yet. The distribution function of the pitch angle also has a large peak around 0, and only the parallel velocity (along field lines) undergoes significant changes. This all points to trapped mirroring particles, and the population mirroring inside or between the current sheets could be a DMLR signature. The trapped population recovered in a configuration without DMLR (initial conditions) presents a different oscillation period and pitch angle distribution.

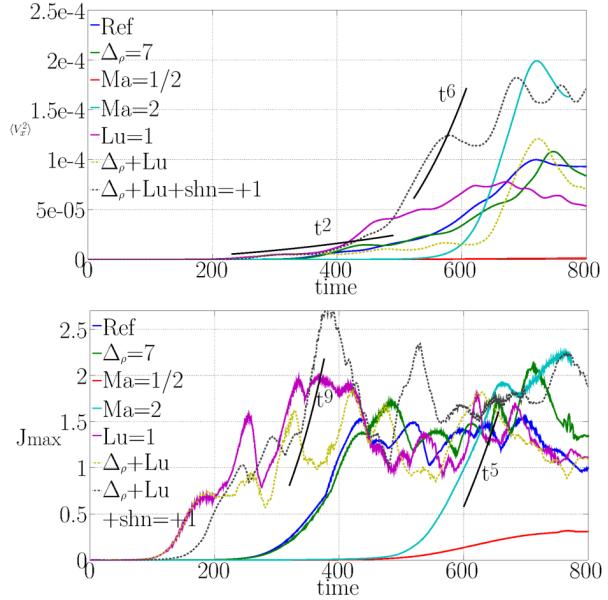


Figure 2: Evolution of the volume averaged current  $\langle \hat{J} \rangle$  against Alfvén time for different alterations of an initial parameter.

This paper presents the study of the KHI at the interface between MS and SW in the attempt to isolate specific signatures that could be found in observational data. The DMLR phenomenon was recovered in an extended time and space setting, with the addition of a density jump and an interacting pair of vortices. This pairing altered by density secondary instabilities deeply affects the topology and intensity of the reconnection sites. The exploration of the influence of the initial parameters led us to identify which ones would interfere with the classical development of the KHI and we concluded that seemingly small changes bringing the simulation closer to a real situation have extensive effects on the development of the instability and the subsequent formation of the boundary layer. The DMLR being tightly dependent of the topology of the flow at the equatorial plane, the reconnection sites are greatly affected too. Since the DMLR is characterized by two reconnection regions, specific signatures of their presence found in our simulations should be recorded by spacecraft. The field data show that the DMLR is compatible with the formation of the Kelvin-Helmholtz vortices. The particle results show that specific bouncing populations should appear in the spacecraft data.

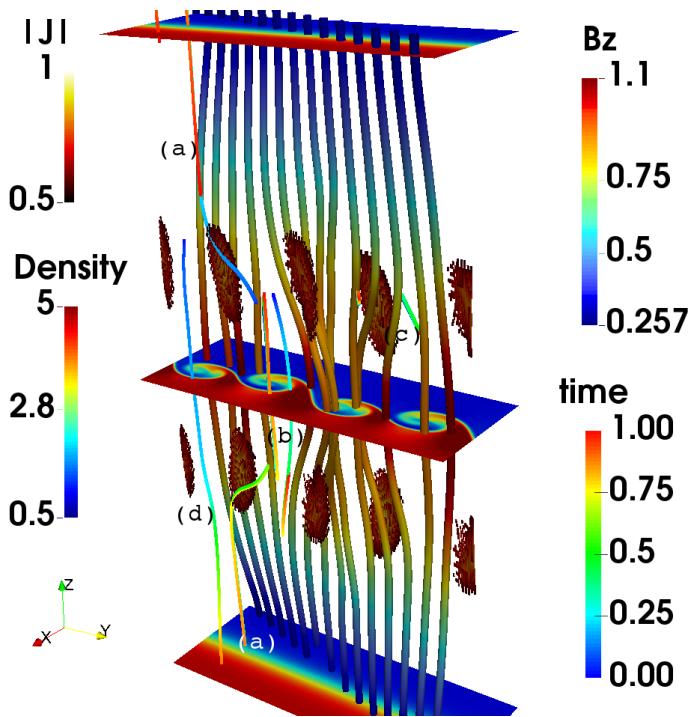


Figure 3: Time coloured trajectories of different particles.

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