Hall-MHD simulations of the Kelvin-Helmholtz instability at the magnetopause: reconnection and transport of the northward solar-wind

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The process feeding the development of a large boundary layer at the interface between the solar wind (SW) and the magnetosphere (MS) during northward interplanetary magnetic field is still not fully understood, though the theory stating the Kelvin-Helmholtz instability (KHI) as the major actor has a good agreement with observations so far. In this contribution, we study the different configurations than can occur in the KHI scenario in three-dimensional (3D) Hall-MHD setting, where it is known to trigger the double reconnection at mid-latitude (DRML) process exposed by Faganello, Califano et al. [1]. It 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. The first side of this contribution intends to assess the influence of various parameters on the growth rate of the KHI and thus the efficiency of the DRML and the second part aims at identifying signatures of this process that could be compared to data gathered by spacecrafts. The plasma at the SW/MS interface can be sufficiently described by the resistive Hall-MHD set of equations. The introduction of the Hall term aims to take into account the possibility 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 the Earth's near space, leading to an additional current term, while the magnetic resistivity will allows for the plasma to break fields lines and therefore account for reconnection processes. These contributions appear explicitly in the Ohm's law $\mathbf{E} = -\left(\mathbf{v} - \frac{\eta_H}{\rho}\mathbf{J}\right) \times \mathbf{B} + \eta \mathbf{J}$, which has been rewritten to make the parameter $\eta_H = \frac{\rho}{n_e e}$ appears beside the magnetic resistivity η. We also uphold $\nabla \cdot \mathbf{v} = 0 = \nabla \cdot \mathbf{B}$ in our set of implemented equations. They use of the momentum density $\mathbf{m} = \rho \mathbf{v}$, the total pressure $p = p_{thermal} + \frac{B^2}{2}$ and the current $\mathbf{J} = \nabla \cdot \mathbf{B}$ and are normalized by using the ion mass m_i, the ion inertial length δ_i = 100 km and the ion cyclotron frequency Ω_{ci} = 0.3 Hz. This results in an Alfvén velocity of 150 km/s and a normalizing magnetic field of B = 20 nT. The simulation is initiated with same field used in [1] derived from the solution of a simplified Grad-Shafranov equation and the velocity, magnetic fields and density are then derived from that vector potential. The box size is chosen larger than in [1], enough for two pairs of KH vortices to appear

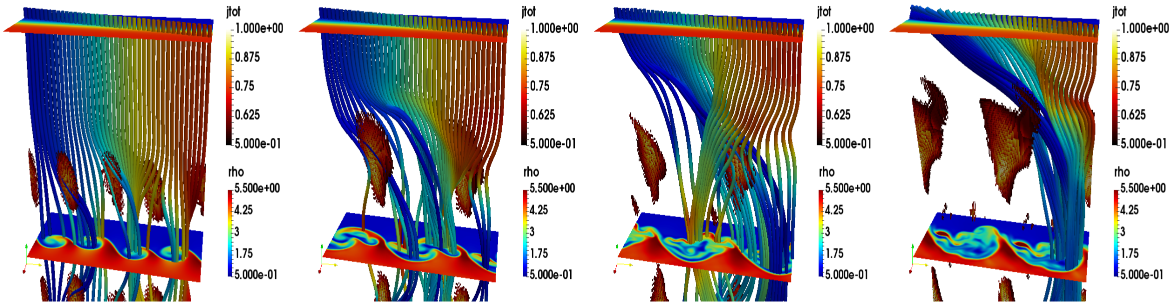

Figure 1: *Snapshot of the time evolution of our simulation. From top left to bottom right :* t_A*=400 (rolling-up),* t_A*=500 (mixing layer and strong current) ,* t_A*=600 (DMLR occurred),* t_A*=700 (DRML keep occuring).*

since in real situation there would be many vortices interacting and their interaction is as much important as the existence of a single one. The usual resolution of the simulations are $N^3 = 200^3$ and the boundary conditions are periodic in the y and z-directions, while they are transparent in the x-direction. These conditions still correctly describe the situation as long as the field variations at far distances from the equator remains almost unaffected. This holds true up to t_A=700 (see Fig. 1) which is much further than the previous study. The other significant parameters set at the initialization of the simulations are the Alfvén Mach number M_A= 1, the sonic Mach number M_c=1, the plasma 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 $\gamma = \frac{5}{3}$. The Fig. 1 present 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 (middle 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 (shown in dark to white for current magnitude), 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 the fields lines together (t_A=700). The resulting effect is that a certain amount of matter and energy is regularly and almost instantaneously exchanged between the two different plasmas as a consequence of a change in the magnetic topology without actual matter flow or transport. It is important to mention that this configuration can depend heavily on the physical parameters, as shown in Nykyri et al. [2] 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 $<\hat{J}>$ against physical time. The twisting and compressing of the field lines leads to the emergence of current sheets of variable widths and intensities, and since we are interested in potential reconnection sites, this figure can point us by an overall manner toward which of the parameters should be examined further. If we focus on the effect of varying the initial density jump from $\Delta n = 4.7$ to $\Delta n = 7$, increasing the density imbalance does not affect the growth rate of the instability but it increases the maximum value of $<\hat{J}>$ 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 Taylor-Rayleigh instabilities due to the centrifugal force of the vortices. A more realistic value would be $\Delta n = 9$ increasing the effect described here. When we interest ourselves in the effect of the shear layer L_u, we see that the KHI develops two times sooner than for L_u=3 and the growth rate is a little higher but the other obvious conclusion is that the averaged current $<\hat{J}>$ reaches again a much larger value. In the same fashion we look into the influence of the Hall term by varying the magnitude of η_H present in Eq. , although in reality it is determined by the environmental physical quantities. The additional term inhibits the extension and intensity of the current sheet. At the opposite of the previous effect, the study on the resolution demonstrate 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. Starting around t=1000 in Fig 3, 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 alternance between SW and MS values of the density and Alven velocity. The scope of this paper can be summed up as the study and beginning of the characterization of the different aspect 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 DRML phenomenon was recovered in a time and space extended setting, with the addition of a density jump and a second pair of vortices pairing with each other. This pairing altered by den-

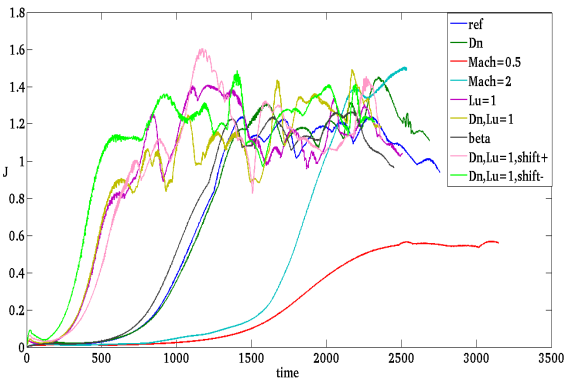

Figure 2: *Evolution of the volume averaged current $<\hat{J}>$ against Alfvén time for different alterations of an initial parameter.*

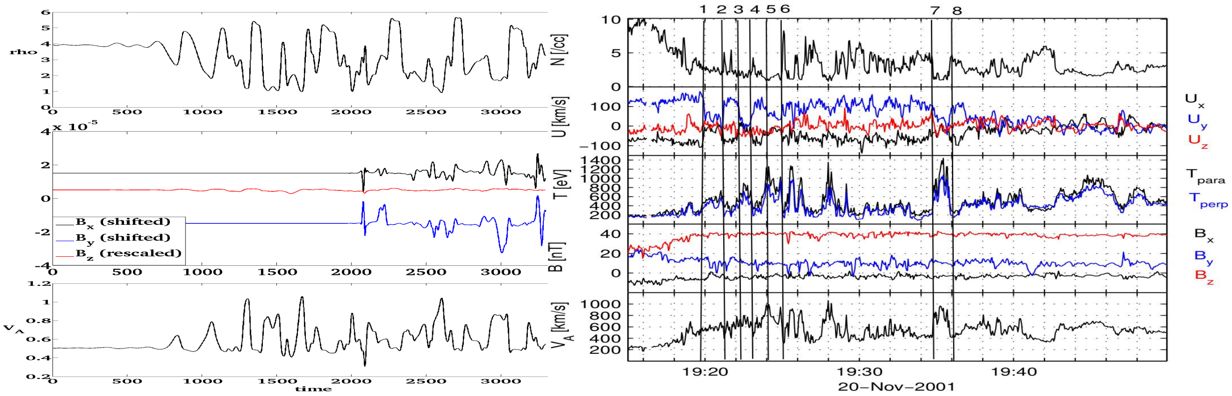

Figure 3: *Left : data from a point close to the interface SW/MS. Right : Data gathered by Cluster (Figure taken from Rossi's thesis [3]).*

sity secondary instabilites 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 greatly interfere with the classical development of the KHI. We could conclude that seemingly small changes, that bring 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 DRML being tightly dependent of the topology of the flow at the equatorial plane, any variations can greatly affect the reconnection sites and rate. Further, on one hand we demonstrated that the Hall-term has a inhibiting effect on the width and intensity of the current sheets. On the other hand, this conclusion is balanced by the fact that the same width and intensity are much larger when the simulation are better resolved. This also indicates that more efforts must be put into the efficiency of our scheme toward high resolution Hall-MHD computations. On that note, further development of the code is undertaken, as well as better identification tools for the reconnection and a more efficient Hall-term solving scheme. This would allow to study the cases exposed here in more details, as well as improving the analytic setting to make the initial and boundary conditions closer to the reality, in order to improve the comparison with observational data and the identification of specific KHI and DRML signatures.

References

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