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HALL-MHD SIMULATIONS OF THE KELVIN-HELMHOLTZ INSTABILITY AT THE SOLAR WIND/MAGNETOSPHERE INTERFACE

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Abstract. The process feeding the development of the 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 Kelvin-Helmholtz instability (KHI) being the major actor is in good agreement with the observations so far. In this work, we study different configurations than can occur in the KHI scenario in a three-dimensional (3D) Hall-MHD setting, where the double mid-latitude reconnection (DMLR) process exposed by Faganello, Califano et al. is triggered by the equatorial roll-ups. Their previous work is extended here with a larger simulation box and the addition of a density contrast. The influence of the parameters on the growth rate of the KHI and thus the efficiency of the DMLR is assessed. The effect of the Hall term on the physical processes is also investigated.

Keywords: solar wind, magnetosphere, Kelvin-Helmholtz, Hall-MHD

1 Introduction

The plasma at the SW/MS interface is described by the resistive Hall-MHD set of equations. The introduction of the Hall term take into account the possibility that ions can demagnetise at the ion inertial length $\delta_i = c/\omega_{pi} \approx$ 100 km and break the 'frozen-in' condition, leading to an additional current term, while the magnetic resistivity will allows for the plasma to break fields lines and account for reconnection processes. These contributions appear explicitly in the Ohm's law $\mathbf{E} = -(\mathbf{v} - (\eta_H/\rho)\mathbf{J}) \times \mathbf{B} + \eta\mathbf{J}$, which has been rewritten to make the parameter $\eta_H = \rho/(n_e e)$ appears. The KHI will develop faster around the equatorial plane as the shear between the SW and the MS is stronger in this region, after the dispersion relation from Chandrasekhar (1961). Due to the 'frozen-in' property of the plasma, the differential advection of field lines along the latitude will induce twisting, leading to stressed field lines regions at symmetrical positions on each side of the equatorial plane. This process has been demonstrated by Faganello et al. (2012) and has been branded the DMLR. Magnetic reconnection then happens inside these regions above and below the equatorial plane, exchanging field lines from the MS and the SW with each other, continuously provoking the entry of SW matter into the MS. A specific configuration used by Faganello et al. (2012) will be reproduced here while extending the domain and duration of the simulation to see how vortex mergers in the mid-plane could alter the DMLR. The box size is chosen as L_x=70, L_y=188, L_z=377, given in ion inertial lengths and the number of points in the simulations is $N^3 = 200^3$. L_y is twice larger than in Faganello et al. (2012) so that the domain is large enough for two pairs of KH vortices to appear. The z-direction corresponds to the latitude, the y-direction follows the interface and the x-direction is across the shear layer. The boundary conditions are periodic in the y- and z-directions, while in the x-direction the fields are extrapolated in a continuous fashion and corrected for a discrete monopole control. The initial fields are derived from a solution of a simplified Grad-Shafranov equation with ignorable y-direction that allows for equilibrium at the start and respects the $\nabla \cdot \mathbf{B}$=0 constraint and the velocity field is destabilized by the addition of incompressible perturbations.

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2 Parameters exploration

2.1 Modifications of the initial settings

The value of several initial physical quantities are modified to assert their influence on the growth rate and development of the KHI. The results are summed up in Fig.1 which displays the time evolution of the volume averaged values of V_x^2 and the maximum value of the current J_{max} in the whole domain. This last value is always found the current sheets. The twisting of the field lines leads to the current sheets and is a clue to potential reconnection sites. For M_A=1/2, the lower velocity shear reduces the growth rate of the instability. In the case M_A=2, the instability does not develop as fast as the reference run. However it still appears at a later time with a stronger growth rate and reaches a larger J_{max}. Doubling the density jump to $\Delta_\rho = 7$ allows to determine if secondary RTI compete with the KHI. While the growth rate remains close to the reference run, the maximum current value reached is larger, indicating an enhanced compression of field lines. The last changes are the reduction of the shear layer width and the introduction of a shift between the velocity and density jumps. The result is that the KHI is triggered much sooner for L_u=1, as well as large values of the current, but the final stage displays a lower $< V_x^2 >$, and J_{max} similar to the reference run. This comes from the fact that the velocity perturbation has a greater impact on a smaller and steeper gradient across the shear layer, but the situation becomes similar once the boundary layer between the SW and MS is fully developed. The more interesting point is that the combination of the narrow shear layer and the enhanced density jump on a shifted location yields the largest growth rate and highest values of J_{max}. The time evolution is also more dynamical with large variations in $< V_x^2 >$ and J_{max}.

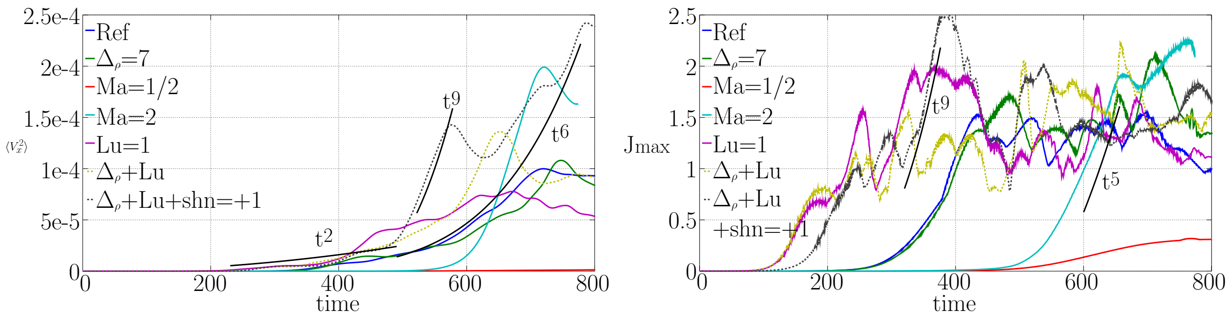

Fig. 1. Left: Time evolution of $< V_x^2 >$ for different alterations of an initial parameter. **Right:** Time evolution of J_{max}.

2.1.1 Initial density jump

We then focus on the effect of the initial density jump in Δ_ρ=[2 3.7 5 7 9]. It allows to clearly identify the effects of potential Rayleigh-Taylor instabilities (RTI), developing and competing with the KHI, fed by the centrifugal force generated by the vortices forming at the interface. All the curves fit the t^6 slope and $< V_x^2 >$ develops at the same time, but it seems to have an optimal value around Δ_ρ=5. It has an effect afterwards as after a similar increase of J_{max} following a t^9 slope, it increases the maximum value of the current found in the domain during the non linear stage. The first element to notice is that the largest values of the current magnitude can be found in the runs with the largest Δ_ρ, up to $J_{max} = 1.3$ compared to $J_{max} = 1.11$ for the reference run. The second point is that this maximum value is not found at the same time between the runs. This comes from the fact that the twisting/reconnection process is quite dynamical in our simulations and that the magnetic gradients, hence the maximum of the current, increase until reaching a value where the reconnection of several field lines happens.

2.1.2 Initial shear layer width

Next is the effect of the modification of the shear layer width from L_u=3 to L_u=1. This will create steeper initial velocity and density gradients and cause the KHI to appear faster than for the reference setting even keeping the other parameters at their reference values, and this is confirmed by Fig.3. The KHI and current sheets appear much sooner for L_u=1 than for L_u=3 and the first one reaches current values 30% higher even before the L_u=3

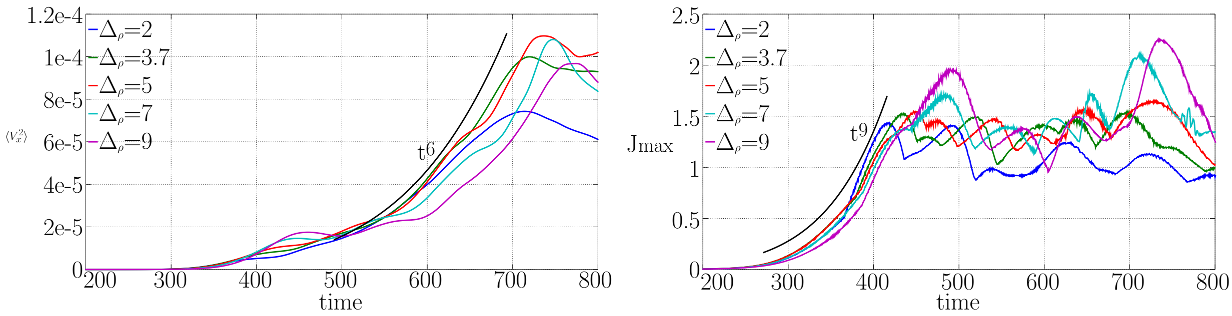

Fig. 2. Left: Time evolution of $< V_x^2 >$ for different Δ_ρ. **Right:** Time evolution of J_{max}.

run reaches its first maximum. Nevertheless, the picture changes after some time as the L_u=1 simulation, while still reaching larger current values than the reference run, reaches its value maximum of $< V_x^2 >$ around t_A=600 and remains at a lower value than the reference run. What can be observed here is that the boundary layer is formed faster for L_u=1 and saturate in its non-linear evolution but since the current values are equal or higher than for the reference run, it shows that the $< V_x^2 >$ and J_{max} are not linked in a simple way, but that the magnetic topology induced by the flow variation at the linear stage has consequences at later stages even if the general process remains the same in both cases. The L_u=2 run presents a most interesting variation of this development since it displays the fastest and largest growth of $< V_x^2 >$ while reaching values of J_{max} no larger than the reference run in the linear stage. But at later stages after a drop in current magnitude and then in velocity, both increase to the largest values reached by the simulations in this set, showing a restart of the braiding/reconnection process. The addition of the shift between the velocity and density jump has a more diverse effect on the KHI evolution. The run with a negative shift see the KHI developing sooner than any other simulations but then saturates after its initial surge in a similar fashion to the L_u=1 run. The positive shift has quite the opposite effect as it seems to start the same way the L_u=1 run does, then reaches very large values of $< V_x^2 >$, becoming similar to the L_u=2 run, and presents a J_{max} evolution with the largest variations.

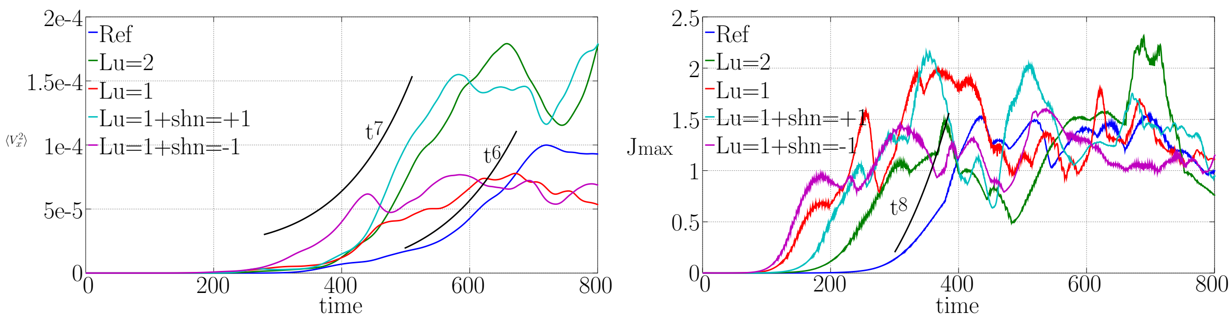

Fig. 3. Left: Time evolution of $< V_x^2 >$ for different L_u. **Right:** Time evolution of J_{max}.

2.2 Influence of the Hall term

We also look into the influence of the Hall term by varying the magnitude of the parameter η_H in Ohm's law. The actual normalized value the parameter should have in our setup is $\eta_H = V_{A0}/(\Omega_{ci0}\delta_i)$=6.25. Previous studies argued that the Hall term usually enhances the instability and transport properties of the flow like Chacón et al. (2003). This trend is confirmed in Fig.4, where the more realistic η_H=6.25 case attains almost twice the maximum value of $< V_x^2 >$ presented by the other simulations. The growth rate in this case is also much larger than for the lower values of η_H following a t^6 slope. Despite this enhancement of the flow in the x-direction, all Hall-MHD simulations share the same effect on the current magnitude. This influence of the Hall term on the current is backed by Fig.4 where the maximum value of the current decreases steadily with the increasing value of η_H while still retaining roughly the same evolution.

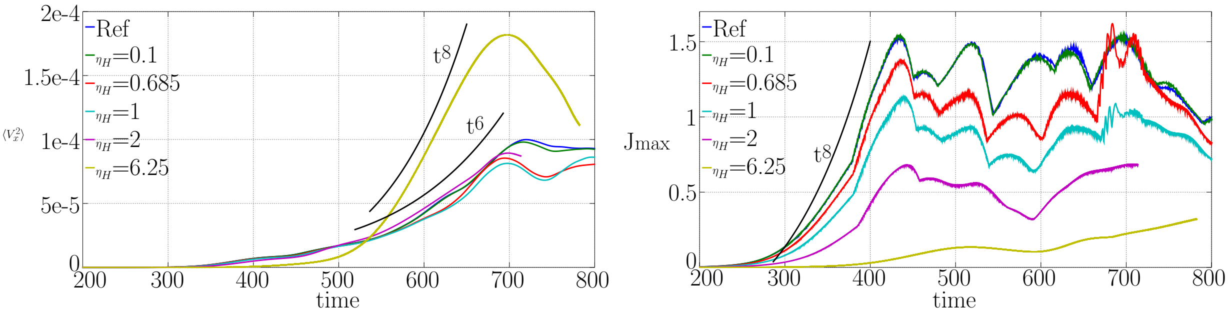

Fig. 4. Left: Time evolution of $< V_x^2 >$ for different η_H. **Right:** Time evolution of J_{max}.

3 Conclusions

The Kelvin-Helmholtz instability is one of the best candidate to explain the expansion of the low-latitude boundary layer forming between the shocked solar wind and the magnetosphere during northward IMF as more and more theoretical and observational studies points out. However, the precise characteristics of the mechanism remains unclear. The development of vortices on the equatorial plane do not only affect the boundary layer at this location but can also have consequences for the SW/MS interface at a distance as the DMLR hypothesis shows. In this paper we experimented on the different configurations the DMLR can adopt depending on the initial value of different physical parameters. The first observation is that the density contrast, neglected for the sake of clarity in many previous works, is an important feature of the KHI in those conditions. It can greatly affect the profile of the boundary layer, and by extension the efficiency of the DMLR as an exchange mechanism for field lines, and thus matter, between the SW and the MS. The second point is that the initial width and location of the shear layer and density contrast have a significant effect on the growth rate and size of the emerging boundary layer between SW and MS, again notably affecting the mixing on the equatorial plane and the topology of the current sheets at mid-latitude. At last some attention must be kept on the influence of the Hall term and the resolution used in simulation. Though the enhancement of the growth rate of the instability by the Hall term is recovered, it presents here an inhibiting effect on the magnitude of the current sheets, while not affecting much the general topology of the flow. A more detailed analysis, also including the effect of the resolution and the simulation of spacecrafts data can be found in Leroy & Keppens (2016).

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